THE ENGINES OF THE HUMAN BODY

BEING THE SUBSTANCE OF CHRISTMAS LECTURES GIVEN AT THE ROYAL INSTITUTION OF GREAT BRITAIN, CHRISTMAS, 1916–1917

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BY

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WORKS BY

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THE ANTIQUITY OF MAN

New and Enlarged Edition

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THE HUMAN BODY

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PREFACE TO FIRST EDITION

In this book I have sought to place before the general reader a concise, fresh, and plain account of the human body. The circumstances under which it was written serve to explain the nature of its contents. Its chapters represent the substance of a course of lectures I had the honour to give to the audience of boys and girls, men and women, who greet a Christmas lecturer at the Royal Institution. On such an occasion the technical terms used in a medical college are out of place; the lecturer has to find a way of giving a simple explanation of a machine which is so complex that it needs almost a dictionary of new, and often uncouth, words to name its various parts and workings. Mere simplicity of language, however, will not meet all the difficulties of such a situation. The lecturer must discover and use a fresh machinery for the display of old facts, one which will give opportunities of unveiling, in their proper place and perspective, the more recent advances made by anatomists and physiologists. For that reason I went to the workshop of the engineer and selected examples of his inventive ability to illustrate the creative genius displayed by Nature in the construction of the human body. Hence the machinery of our bodies is regarded in this book from a somewhat novel point of view—that of the mechanical engineer. Further, in approaching these lectures I had the feeling that I should weary my audience, as I certainly should my reader, were

I to follow the custom of medical colleges by describing the machine I had to explain in a series of fragments. I therefore introduce the reader to the human body in its entirety—as a complete, living, and moving machine. In all of these three respects, I believe, this work differs from its numerous predecessors.

While I have made my main appeal to the general reader—to the man or woman who desires to know what modern medical teachers think of the marvellous contrivances of the human machine,—I hope that the account here given of the human body may also appeal to medical men and to professional engineers.

I hope, too, that students of Medicine and of Biology, as well as lecturers and teachers who have to impart an elementary knowledge of human Physiology, may also find assistance and guidance from its pages.

I am glad to have this opportunity of thanking Sir James Dewar of the Royal Institution for much helpful counsel, and of acknowledging my indebtedness to Sir Thomas Wrightson, Bart., M.Inst.C.E., and to Mr Allan A. C. Swinton, F.R.S., M.Inst.C.E., for reading over the proof-sheets of those chapters which deal with mechanical and electrical contrivances.

ARTHUR KEITH.

October 13th, 1919.

PREFACE TO SECOND EDITION

KNOWLEDGE of the human body never stands still ; every year sees an increase. Even books, such as this, which deal merely with elementary facts are soon in need of revision. Although only five years have come and gone since I wrote out lectures originally addressed, during war time, to a "juvenile auditory," yet I find it now necessary to expand certain growing subjects and here and there to amend others. But I have left the original text almost as it stood, except as far as verbal and other minor alterations are concerned, preferring to introduce new matter, dealing with recent advances in our knowledge of the human body, as a series of appendices placed at the end of this edition. A list of the appendices follows this preface ; they represent the directions in which Anatomy and Physiology are expanding at the present time. Guidance to each appendix is given in the section of the text to which it refers. All additional matter has had the advantage of passing under the vigilant eye of my friend, Prof. H. E. Armstrong, F.R.S.

ARTHUR KEITH.

ROYAL COLLEGE OF SURGEONS,
January 25th, 1925.

LIST OF APPENDICES

APPENDIX — PAGE

A. Sir James Dewar 276

B. Muscles as combustion engines, and how they serve the needs of athletes 276

C. How muscles are controlled and educated 287

D. Can cartilage cells become bone-builders? 292

E. The nourishment of cartilage 294

F. The output of the heart 295

G. Breathing, thinking, and health 297

H. Vitamins 308

J. The origin of petroleum, the heat values of food, and the work efficiency of the human body 312

K. The effects of civilisation on man's body 317

L. Insulin and hormones 321

M. The human body as a society of microscopic units . . . 326

N. Automatic nerve exchanges 329

CONTENTS

CHAP.		PAGE
1.	HOW THIS BOOK CAME TO BE WRITTEN . .	1
2.	THE MUSCLES, WHICH ARE THE MOTOR ENGINES OF THE HUMAN BODY, COMPARED TO THE ENGINE OF A MOTOR CYCLE. THE ENGINES WHICH MOVE THE LEGS IN WALKING .	8
3.	HOW THE BACKBONE IS BALANCED AS WE SIT, STAND, OR WALK, AND SOME POINTS OF DIFFERENCE BETWEEN THE MOTOR CYCLE AND HUMAN BODY	21
4.	ARE OUR MUSCLES REALLY INTERNAL-COMBUSTION ENGINES?	28
5.	MUSCLES ACT AS RECIPROCAL ENGINES, BUT IT TAKES YEARS TO LEARN HOW TO MANAGE THEM	39
6.	THE BONES OF OUR BODY ARE LIVING LEVERS. THE SKULL, BESIDES CONTAINING THE BRAIN, SERVES AS A LEVER OF THE FIRST ORDER .	47
7.	THE FOOT AND THE FOREARM AS LEVERS .	57
8.	BONE-BUILDERS AND THE MANNER IN WHICH THEY CONSTRUCT LIVING LEVERS . .	69
9.	A PERFECT LUBRICATING SYSTEM . . .	80
10.	WHAT HARVEY WAS TAUGHT CONCERNING THE HEART	89

CHAP.		PAGE
11.	HOW HARVEY DISCOVERED THAT THE HEART IS A DOUBLE PUMP	97
12.	HOW A "HEAD OF PRESSURE" IS MAINTAINED IN THE ARTERIES	108
13.	A PAIR OF LIVING BELLOWS	120
14.	RESPIRATORY CHAMBERS	133
15.	CONTRIVANCES FOR REGULATING THE HEAT OF THE HUMAN MACHINE	146
16.	A SURVEY OF THE WORKSHOPS AND LABORATORIES OF THE HUMAN BODY, WHERE FOOD IS TURNED INTO FUEL FOR THE TISSUES	159
17.	A TRANSPORT SYSTEM OF A PECULIAR KIND	170
18.	THE REGULATION OF A FACTORY FOR THE PREPARATION OF TISSUE-FUEL	181
19.	THE BIGGEST AND BUSIEST FACTORY IN ALL THE BODY	194
20.	A FACTORY THREATENED WITH DECAY	207
21.	A POSTAL SYSTEM OF A PECULIAR KIND	220
22.	THE MASTER CONTRIVANCE OF THE HUMAN MACHINE	232
23.	UNCOVERING THE MACHINERY OF THE BRAIN	243
24.	AUTOMATIC TELEPHONE EXCHANGES	252
25.	IN THE REPAIRING SHOPS	267
	INDEX	334

LIST OF ILLUSTRATIONS

PLATE I.—The walking human skeleton (Albinus) . . *End of book*

PLATE II.—The muscles of the human body (Albinus) . „

FIG. PAGE

1. A diagram to show the parts of which an internal-combustion engine is made up 10

2A. Charge stroke 12

2B. Compression stroke 12

2C. Driving stroke 12

2D. Exhaust stroke 12

3. Plan of vertebræ in the lower or lumbar part of the spinal column. (A) A lumbar vertebra looked at from above to show its levers; (B) Three lumbar vertebræ showing the discs between them which act as buffers 24

4. A drawing of the biceps of the right arm showing its tendons, its vessels, and its nerve 29

5. (A) A primitive muscle fibre or cylinder in an uncontracted state; (B) A cylinder in a state of contraction with its nerve fibre 35

6. Showing the manner in which capillaries are arranged among muscle cylinders 37

7. Showing the anterior brachial muscle which flexes the forearm, and the posterior brachial or triceps which extends it . . 42

8. Showing the brachial and triceps muscles replaced by internal-combustion engines 42

9. Showing a chisel 10 inches long used as a lever of the first order 48

FIG. PAGE

10. The skull as a lever of the first order 50

11. (A) The opening in the base of the skull, by which the brain stem passes to the spinal canal; (B) The parts of the socket on the ring of the atlas 53

12. (A) The original parts of the first or atlas vertebra; (B) Showing the "body" of the first vertebra fixed to the second, thus forming the pivot on which the head turns 55

13. Showing a chisel used as a lever of the second order . . 58

14. The bones forming the arch of the foot, seen from the inner side 59

15. Showing the crank-pin of an engine at: (A) First dead centre; (B) First maximum leverage; (C) Second dead centre; (D) Second maximum leverage 61

16. The arch of the foot from the inner side, showing some of the muscles which maintain it 63

17A. A chisel used as a lever of the third order. (W) Weight; (P) Power; (F) Fulcrum 65

17B. The forearm and hand as a lever of the third order . . . 66

18. Showing the action of the brachialis anticus in the arm of an anthropoid ape 67

19. In this figure the following sections of the thigh-bone at various stages of growth are shown:—Section of the thigh-bone at birth to show its structure. Its lower end enlarged to show the centre of ossification and trail of blood-vessels. Section at the fifth year. Section at the fifteenth year. Section at the twenty-fifth year 71

20. An X-ray picture to show the design or construction of the upper end of the thigh-bone 76

21. The construction of the upper end of the thigh-bone, as depicted by Professor F. Dixon, compared with a drawing of Fairbairn's crane (W. Finerty) 77

22. (A) The upper end of a thigh-bone at the fifth year, above which is indicated the position which the head and neck will occupy when the fifteenth year is reached; (B) The form which the upper end of the femur would assume if there was no remodelling 78

23. A vertical section of the ankle-joint, exposing the lower end of the tibia and astragalus 83

NO. PAGE
24. A magnification of the part of the ankle-joint cartilage indicated by the line A shown in fig. 23 83

25. A diagram to illustrate what Harvey was taught concerning the veins and arteries 92

26. A diagram to illustrate what Harvey was taught concerning the use of the heart 95

27 (A) A swelling on a vein indicating the presence of a valve within it; (B) The vein laid open, showing the valves partly open; (C) Showing the valves shut 98

28. A diagram to show the four chambers of the heart and the valves which guard their openings 101

29. The various parts of a force-pump (A) compared with the parts of the left ventricular pump (B) 110

30. A terminal artery, surrounded by muscle fibres, ending in a network of capillary vessels 116

31. To show the manner in which the 7th rib and the muscles attached to it help in expanding the thorax 126

32. A vertical section of the human thorax exposed by removing the front wall 130

33. The air passages in the nose, throat, and mouth exposed . . 135

34. A cluster of air or respiratory chambers, with a bronchiole leading to it 140

35. A cluster of air chambers with blood-vessels applied to them . 140

36. An inverted glass-funnel, in which a lighted candle has been placed, set upon a movable diaphragm 151

37. Diagram showing a bolus of food within the pharynx, in the act of being forced into the œsophagus 176

38. A segment cut out from the œsophagus and laid open to show a bolus in transit. (A) A small fragment of the outer muscular coat magnified to show the individual spindle-shaped fibres of which it is composed in a relaxed state; (B) Fibres or spindles greatly enlarged to show a contracted state . . 177

39. An X-ray shadow of the full stomach, with contraction waves passing towards the pylorus 182

40. The stomach laid open to show the cardiac and pyloric gateways 185

FIG.		PAGE
41.	Part of the duodenum, with pancreas and bile duct . . .	200
42.	Section *a* across a part of the wall of the small bowel showing the structure of a villus; the tubular glands and lining epithelium are also represented	205
43.	Shadow of the great bowel twenty-four hours after a bismuth breakfast	208
44A.	The cæcum covered by its outer or peritoneal coat . . .	212
44B.	The cæcum, appendix, and ileo-cæcal orifice laid open . .	212
45.	(A) The brain and spinal cord exposed from the right side; (B) The brain stem, showing the origin of the cranial nerves; (C) Section across the spinal cord showing the manner in which the spinal nerves arise by two roots	236
46.	Plan showing the corresponding elements in a telephone and in a nerve system. (A) Unit of a telephone system; (B) Unit of a nerve system	255
47A.	The arrangement of two units in an exchange of a telephone system	258
47B.	The arrangement of two units of an exchange in the nerve system	258

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No. 1492
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THE ENGINES OF THE HUMAN BODY

CHAPTER I

HOW THIS BOOK CAME TO BE WRITTEN

There is a machine which every one of us has to drive morning, noon, and night, day by day, year in and year out, until the end of life's journey. So quietly does this machine run, so easy is it to guide, that we never imagine it as contrived in the same way as the machines which clever men have invented and made—machines which can run, fly, weave, sew, count, and even speak. These machines made of metal or of wood seem so different from our bodies; they are fed with coal or oil, or electricity; they become very hot when they work and very cold when they stand idle; they never feel pain, laugh, cry, play, or know what it is to have a good time. Some of these machines are wonderfully made, complex, and really difficult to understand; but not one of them, not even the most intricate, is so hard to understand as the human machine—your body and mine. You will see how difficult it is to find out how its parts work when I tell you that for two thousand years and more a countless succession of clever men have studied it, both when it was living and when it was dead, have taken it to pieces—or, as medical students say, have dissected it—have examined its flesh and textures with the most powerful of microscopes, have applied to it all the arts and crafts known to chemists, and

yet after all these centuries of labour, after all the fine books which anatomists have written, we have to confess that we have not nearly mastered all the secrets of the human machine. But we have learned a great deal, and it is about some of the more wonderful discoveries which man has made concerning his own body that I am to write about in this book. It may take many thousands of years more, but I am certain that if we apply ourselves to its study as anatomists and physiologists have done and are doing, the time will come when we shall understand the human body—how it feels, sleeps, wakes, plays, and works—just as perfectly as we know the machinery of the steam engine which pulls a railway train or the internal-combustion engine which drives a motor bicycle.

I have been telling you what this book is to be about before I have mentioned a circumstance which seems to me important—how it came to be written. That happened in this way. One morning in September 1916 I received a letter which threw me into a flutter; it was from the Managers of the Royal Institution in London, telling me that Sir Wm. Bragg, who was to have given the Christmas Lectures to "a juvenile auditory," had been called away on urgent work connected with the great war and at the same time inviting me to take his place. Now when I looked over the long list of names of the great and famous men who had given these lectures in past years, especially when I remembered that it was the wonderful magician Michael Faraday who had set the pace, as it were, my courage began to fail me. Long ago, when men and women who are now very old were boys and girls, Michael Faraday showed them, at these Christmas Lectures, his marvellous and beautiful experiments and divulged the secrets he had discovered—secrets which electrified the world—in words and sentences which every boy and girl in his crowded audiences could understand. But then Faraday was especially fortunate in this way; he was not only a genius but he had grown old without becoming "grown-up," and knew how to tell things so that the young thought he was one of themselves. Now when I

called to mind all of these things, especially when I remembered that I had no fresh experiments to show, no new discoveries to confide, and that I was terribly grown-up, I almost made up my mind to write to the Managers and refuse the honour of giving the Christmas Lectures.

But one thought stopped me. Just at that time more than a million human machines, all of them made in Britain or in British colonies, were fighting grimly and freely giving their lives in foreign lands that we and our children might have homes and freedom. It was a serious time then; men and women were hungry for real knowledge, not fairy stories. So I thought: Why not tell them something of the story of the human body—the human machine? Is it not the machine which you have been labouring at and trying to understand for thirty years and more? Are you ashamed of the things you have been teaching day after day to a succession of medical students? Will not boys and girls grow into wiser, perhaps happier, men and women if they know about the machinery of their own bodies? When these thoughts passed through my mind, I gladly accepted the invitation and resolved to give the coming Christmas Lectures on the Human Machine.

One great difficulty had to be got over. I could not carry an actual human body to the Royal Institution and take it to pieces before the happy children who gathered there at Christmastide. I saw in my mind's eye the front rows of the great amphitheatre filled with the radiant, brightly lighted faces of boys and girls aged 10 or 12; in the rows behind them their elder brothers and sisters aged 15 and 16, and away on the higher tiers and filling the upper galleries, the faces of men and women who years before had occupied and enjoyed the front rows of the amphitheatre. Clearly it was impossible to do before such an audience what is done every day in medical colleges. So with the help of some of my assistants at the Royal College of Surgeons we set to work, and out of coloured cardboard made a real Goliath skeleton, one with all its bones truly shaped, and with real joints, so that the skull could move on the

spinal column, and the bones of the arm and leg work just as in life. Then we fitted out the skeleton with muscles, the structures or engines which move the bones in walking, breathing, and eating, and which make up the soft parts or flesh of the body. We also provided this cardboard Goliath with a heart or blood-pump; arteries by which the heart could pump the blood outwards, and veins designed to bring the blood back to the heart, were also provided and set in place. A windpipe or trachea was fitted to bring air from the nose to the lungs, which were duly placed within the chest. A mouth, tongue, jaws, teeth, œsophagus, stomach, and intestines were fitted into their proper places. Goliath was given a brain, a spinal cord, and a full set of nerves. He was given eyes, ears, and a nose, and then, to make him quite complete and comfortable, a covering of skin. We foresaw that even in such a Goliath the heart, brain, eye, ear, stomach, cæcum and appendix, the joints of his hands and of his feet were on too small a scale to be seen by those who were in the galleries or distant seats of the great theatre. So we made very big models of these parts, and contrived them in such a way that they could be dissected and thus be taken to pieces. By this means the manner in which small parts of the human machine worked could be seen and understood by those who did not come early enough to get a front seat. Then, too, in order to make it quite clear that the machinery of the human body does work on the same plan as that of the machines which engineers turn out, we had to make large working models of the small engine—an internal-combustion engine—which drives a motor cycle, for, as we shall see, the human machine is furnished with many motor engines, only we call them muscles—not engines. We had to make models of various kinds of pumps, of bellows, of telephone exchanges, and of many other contrivances and inventions. And so it came about that when the children and the "grown-ups" crowded into the spacious, brightly lighted theatre of the Royal Institution on the afternoons of that Christmas season they

had before them a full family of mechanical Goliaths. They became familiar with the models and, on the whole, rather liked the way they moved, worked, and showed their secrets. Sometimes the boys, and even the girls, laughed or clapped their hands. Sometimes, too, they were just a little bored, but not many ever went to sleep. And so the lectures went merrily enough, and when they were over some of the "grown-ups" said to me that I should write them down and make a book of them. But at that time the country was in trouble, and men had no heart to write books—only to fight. I promised to make a book of them when peace came. And now that peace has come I have sat down to make my promise good. That is how this book has come to be written.

Hence it is that as you read these pages you must imagine that it is Christmas time and that you are in the theatre of the Royal Institution, young again and wishing to know about living machines, only there will be certain things that we shall miss; there will be no Goliath models to show us how muscles act as engines and bones as levers, or how the piston of an engine is driven by exploding a mixture of petrol and air. We have to use in place of our working models imperfect sketches and simple drawings, needing many words to make their meaning clear. Nor shall we be able to call in the willing aid of Mr Heath who so quietly and unobtrusively helps a lecturer through the mazes of his Christmas task. Nor will you forget that, not far away, there is certain to be one who is handing down in the Royal Institution the soul and spirit which Faraday left there and who is sure to be waiting for the lecturer at the end of every hour, encouraging him, perhaps even scolding him if he has not made his meaning clear, just as he did during that Christmas which now seems so long ago.[1]

Now it so happened at the time I gave these lectures most of us who stayed at home became poorer, but there were some who became richer than ever they were before. That is what always happens in wartime, and we saw it occur in the great war which was then raging. We all

thought that the only people who should become rich were the families and the men who gave their lives for our country, but we could not find out a plan that would bring that about. But I hope the boys and girls for whom I am now writing—if war should ever come again—will find out a way and put it into practice when they grow up to be men and women. Well, at that Christmas time one of those men who had become very rich had an only son whom he spoiled by giving him everything that he asked for, and as a Christmas gift gave him a new motor cycle of the latest pattern. Now you will scarcely believe me when I tell you that this boy, whom you think so fortunate, was very discontented. He wanted to mount the machine at once and go careering along the streets and roads but could not because he did not know anything about how engines are made, how they work, how they are started or how they are stopped. If I ask you, What is a boy in a case like this to do ?—I think I can guess your answer. You will say that he must seek help from books, consult men who are expert drivers, learn the use of each part—how petrol and air are drawn into the combustion chamber of the engine to form an explosive mixture, how that mixture is fired, and how the force thus set free is made to turn the back wheel with a power that will carry the rider up the steepest hill. You will say that this boy is unreasonable in expecting to be able to work so complex a machine all at once seeing that it has taken thousands of clever men, working through many centuries, to invent and perfect the one which has now come into his possession. I have no doubt that such will be the answer you will make, and I for one shall agree with you. Now it so happens that you and I have been presented with a machine—you only a few years ago, I a great while since—the human machine ; one which you and I have to mount and drive every day of our lives. It is full of the most cunningly contrived inventions ever seen or dreamt of, inventions which have taken millions of years to work out and perfect. Clearly, then, if it is necessary to understand a machine which we mount only

for an occasional hour or day, it is most urgent that we should know something of the machine which has to carry us day after day along the rough but joyous journey of life, *a journey which we can enjoy only if the machine* runs smoothly right to the end. Then, whether we will or no, death will come and dismount us. This is the machine we are now setting out to examine.

CHAPTER II

THE MUSCLES, WHICH ARE THE MOTOR ENGINES OF THE HUMAN BODY, COMPARED TO THE ENGINE OF A MOTOR CYCLE. THE ENGINES WHICH MOVE THE LEGS IN WALKING

When I tell you that I am going to compare the human body to a motor cycle you must think I have gone crazy in putting side by side things which everybody can see to be very different. At least, you will permit me to try and show you how the comparison answers. Let us suppose, then, that it is a fine day in summer, and that you, mounted on a motor bicycle and I on my two legs, have reached a point on a dusty country road where there is a steep ascent straight in front of us for a stretch of miles. We start to climb the hill. Your body is carried to the top in a few minutes by the motor cycle. At a slower pace and on foot I also toil to the top of the hill. There is no doubt as to how your body was carried up. All the time the throbbing engine of your bicycle was hard at work. The engine of the bicycle was the active agent which carried your body up the long, steep hill. Nor is there any doubt about the active agents which carried my body up as I strode after you on foot. All the time certain living structures in my body were actively performing mechanical work, moving my limbs and carrying my body up the hill—doing just the same kind and amount of work as was performed by your bicycle engine. The mere fact that we have given to the active or motor engines of the human body the name of muscles will not blind us to their true nature; they are the

engines which are used in the propulsion of the human machine. I hope that you will agree with me, then, that there is this degree of resemblance between a motor cycle and the human body: each is fitted with a propelling engine or a set of propelling engines.

When we compare the engine which carried you uphill on your motor cycle with those engines or muscles which carried me up on foot, we shall find that they are alike in many ways. As every boy knows, the engine of a motor cycle is a kind of gun, only the chief part of it is called a cylinder, not a barrel. This gun is charged or loaded, not with gunpowder but with an explosive mixture of petrol and air; the explosive mixture is fired, not with a percussion cap but by an electric spark, which enters by the "sparking plug" set in the upper end of the barrel or cylinder (fig. 1). We load a cylinder, not with a bullet but with a piston; were the piston free it would be shot from the cylinder as a bullet is from the barrel of a gun. But the piston is not free; it is tethered by a "connecting rod" to the short lever or "crank-pin" of a shaft or axle which can turn or revolve (fig. 1). Now, when the explosive mixture is fired, the piston or missile being yoked to the shaft spends its force in turning it, instead of shooting free into the air to kill people. And then the main axle of the engine being connected with the hind wheel of the motor cycle turns it and sends the machine forwards. The engine of a motor cycle is thus really a kind of gun which clever men, after endless study and experiment, have made to turn wheels instead of shooting out bullets. Men have found out, too, how to make this kind of gun reload and discharge all by itself, or automatically, so that it can fire two thousand shots or more every minute. We shall find that muscles also reload and discharge automatically.

Presently we shall come to speak of the muscle-engines, and compare them point by point with the internal-combustion engine of the motor cycle. Now you may be familiar with one make of engine and I with another, so in order that there may be no confusion between us I

have asked a friend to draw a simple plan of an internal-combustion engine, built like the model used in my lectures. It is important that we should note all the

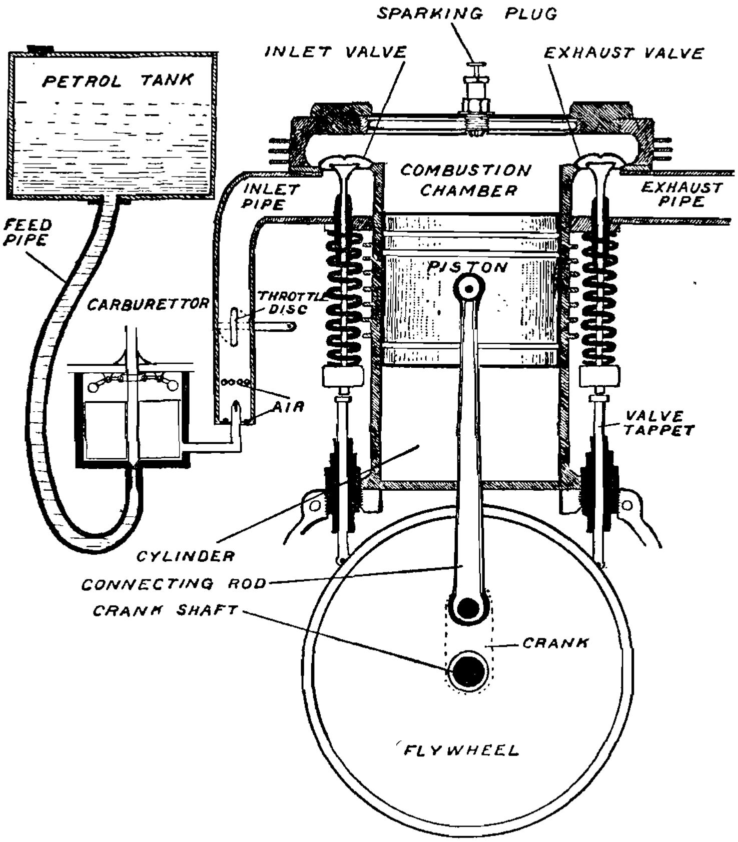


FIG. 1.—A diagram to show the parts of which an internal-combustion engine is made up. The piston is shown at the upper end of the cylinder at the beginning of a stroke—the first downward or charge stroke.

parts, because we shall have to search for corresponding pieces and contrivances in the muscle-engines.

First of all, there is the petrol tank (fig. 1) containing the fuel or food for the engine; a "feed-pipe" runs from the tank towards the upper end or head of the

cylinder. Just before the feed-pipe actually reaches the space in the head of the cylinder known as the "explosion or combustion chamber," there is placed a regulating contrivance or "carburettor." By this contrivance the petrol is mixed with air, and made into an explosive mixture; it has a valve by which the amount of air let in may be increased or decreased. The rate at which the petrol mixture enters the engine is regulated by the "throttle" valve; by opening or shutting it the driver can regulate exactly the rate at which the engine is fed with petrol. The explosive mixture passes into the cylinder by the inlet pipe (fig. 1). Just where the inlet pipe opens into the combustion chamber is placed a valve, which opens to let the mixture in, but once in, the valve becomes closed in a way we need not stop to describe. Then at the opposite side of the explosion chamber there is represented another opening, also guarded by a valve—the exhaust valve—leading into the exhaust pipe (fig. 1). We shall see that, after the explosion takes place, this valve opens and the exploded or burnt gas is forced out through the exhaust pipe. You will note, too, projecting into the head of the cylinder, the "sparking plug" by which the electric spark is discharged and the explosive mixture of petrol and air is fired. I need not remind you that Faraday knew nothing of internal-combustion engines; they were invented long after he was dead, but the dynamo or magneto, which makes the sparking plug a working thing, we owe to the discoveries he made in the workshops of the Royal Institution.

We have now to see how this motor cycle or gun is loaded, discharged, turns the main shaft and drives the hind wheel. We must place ourselves in the position of the inventor who discovered this very wonderful machine. In fig. 1 the piston is shown resting at the upper end of the cylinder, just under the explosion chamber. It fits the cylinder so exactly that if it be drawn down, by turning the crank of the main shaft of the engine, it will act as the piston of a pump, and, supposing the inlet valve to be open, will draw in and fill the cylinder with an

explosive mixture of petrolised air (fig. 2A). If now the piston is made to rise in the cylinder, by turning the crank-pin half a turn more, the petrolised air will be squeezed or compressed at the head of the cylinder and the engine will be thus loaded (fig. 2B). The first downward movement of the piston, which sucks in the petrol mixture, is called the "charge" stroke; the first upward movement which compresses the charge is named the "compression" stroke. Thus two strokes are spent in loading the engine.

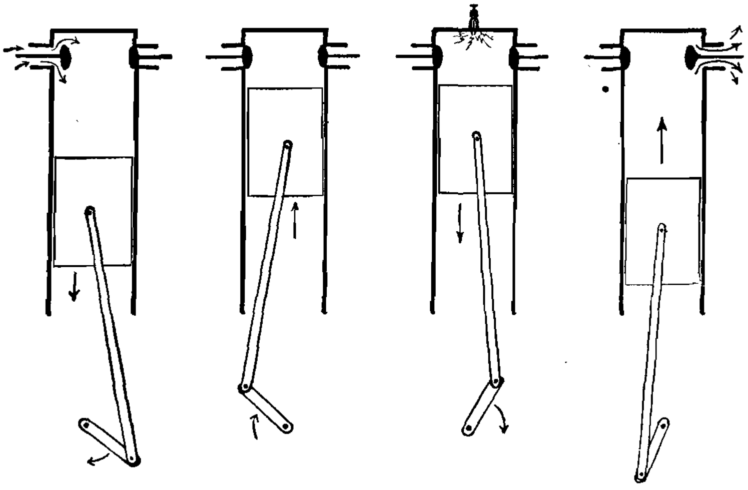


FIG. 2A. Charge stroke. FIG. 2B. Compression stroke. FIG. 2C. Driving stroke. FIG. 2D. Exhaust stroke.

When thus loaded, the charge is fired and the second downward stroke of the piston takes place; it is the "explosion," "effective," or "driving" stroke (fig. 2C). All the driving power of the engine lies in this stroke. With the descent of the piston the cylinder is filled with exploded or burnt gas. It is evident that before the engine can be charged again the burnt gas must be cleared out from its cylinder. The inventor got rid of it most ingeniously by using two devices. He first made an outlet or exhaust and set a valve there which opened automatically as soon as the explosion was over and the driving stroke had

finished. Secondly, he placed on the crank shaft of the engine a fly-wheel which was sent spinning by the driving stroke, and thus, when the driving stroke was over, kept the crank shaft turning and the piston moving. The piston, in its return stroke, acting like the piston of a force-pump, sweeps out the exploded gas from the cylinder through the exhaust valve. Thus the second upward or "exhaust" stroke serves to clear the cylinder (fig. 2D). The moment the exhaust stroke is completed, the exhaust valve shuts, and as it shuts, the inlet valve opens to let in a fresh charge of petrolised air.

The spin or momentum of the fly-wheel, imparted by the "driving" stroke, is not only sufficient to return the piston and sweep out the burnt gases from the cylinder, but is also enough to begin the cycle of strokes again—the first downward stroke which charges the cylinder, as well as also the first upward or compression stroke which squeezes the charge into the combustion chamber. Now here is really a clever invention ; in each set or cycle of an internal-combustion engine there are four strokes, but only one of these—the second downward or explosion stroke—is really effective. The explosion stroke has to do all the work, not only turn the hind wheel and thus drive the bicycle, but has also to empty and to charge the engine. For one stroke the engine acts as a gun ; during the other three it acts as a pump. It was a flash of genius which showed how the effective stroke could be made to perform the other three. But we shall find that Nature in designing muscle-engines has shown even greater genius—a genius so great that we have discovered as yet only some of the secrets and patents of her inventions.

Having thus looked at the plan on which the engine of a motor cycle is made, we are now to set out to see how the engines of the human body are shaped and fixed. They are fixed on a framework of bones known as a skeleton. Any day you may see a motor cycle and make out all the parts of its skeleton, but although men, women, boys, and girls may be seen on the roads or on the streets we cannot see their skeletons for two reasons : firstly because they

are covered by flesh or muscles, and secondly because the flesh is covered by clothes. Of course if we had a dark room and an X-ray outfit we could make the clothes and flesh quite transparent and see every bone of the body, but as most of us have not got these things I have given the picture of a skeleton (Plate I.)[1]—one drawn for a famous anatomist in Holland a hundred and sixty years ago. It is not only drawn very truthfully, but, fortunately for us, it is shown walking—moving its legs just as I supposed mine did when doing that uphill journey. I need not name the pieces of the framework ; each bone is shown with its name attached. But there is one point about the skeleton I must mention here ; we shall find it corresponds not only to the framework of the motor cycle but to the wheels as well. For a wheel is really a number of legs so arranged and so fixed together as to form a circle.

Having run our eye over the framework of the human machine we are now to glance at its muscles or engines. The skeleton seen walking along so gaily in Plate I. appears again in Plate II. fitted out with all its muscle-engines, hundreds in number. The chief ones have had their names attached, but in the meantime we are to concern ourselves with only one of them—the one which makes up the calf of the leg and in the drawing bears two names —gastrocnemius and soleus—although it is but one engine. You will notice that we give names to the engines of the human body just as we do to railway engines. The muscle of the calf of the leg is really a two-cylinder engine—a kind which is often fitted to motor cycles. We can easily see, by looking at Plate II., what the particular use of this engine is. It will be seen to work on the heel ; the heel is its crank-pin. It is the engine which suddenly lifts up the heel as we take a step forward in walking.

We are now to look at the manner in which the muscles which move the heel are fixed to the framework of the body. Engineers are very careful to fasten the engine of a motor cycle very strongly and firmly to the framework

[1] The reader will find the plates inserted at the end of the book.

of the machine. If it were not firmly fixed the strength of the stroke of the piston would be spent in moving the cylinder instead of turning the driving shaft. Firm fixation is needed for the cycle engine, and it is just as essential for muscle-engines. The upper end of the gastrocnemius is fixed so firmly to the back of the thigh bone, just above the knee-joint, by a multitude of fine white fibres fastened into the bone, that even on the strongest effort this fastening or attachment is never torn away. The deeper part of the engine—the soleus (Plate II.)—has the same kind of fastening to the back of the leg bones—the tibia and fibula. Thus the engines which lift the heel work from a firm base formed by the lower part of the thigh bone and the upper parts of the leg bones. Anatomists speak of the basis from which a muscle exerts its power as its "origin," whereas they name the attachment to the lever or "crank-pin" on which the muscle acts, its "insertion." The crank-pin on which the double-cylindered engine formed by the gastrocnemius and soleus acts is the heel; the heel is the crank-pin of the foot which turns or rotates at the ankle-joint. If the muscle acts when the foot is off the ground then it lifts up the heel, and thus tilts the front part of the foot downwards. But if the foot is firmly planted on the ground, as the right foot is in Plate II., then the force of this engine is sufficient not only to raise the heel but also to lift the weight of the body.

In one way the muscle engine differs from a motor cycle engine. If we look at the muscle of the calf of the leg in Plate II. we see that it is yoked to the heel, not by a rigid connecting rod like that which unites a piston to its crank-pin, but by a very strong rope which is called a tendon—the one going to the heel being named the tendon of Achilles, because that ancient Greek warrior is said to have been hung up by the heels. The heel is certainly a crank-pin, and the tendon certainly serves the purpose of a connecting rod, but it is tough and flexible because a muscle is a "pull" engine, whereas all the kinds made by man are "push" engines. A metal

engine exerts its power by pushing the crank-pin, and has therefore a rigid cylinder and a rigid piston-rod ; flesh engines exert their power by pulling, and changing their shape all the time ; they have flexible piston-rods which we call tendons or sinews. Think for a moment what would be the case if our bodies were fitted out with rigid push engines instead of the soft, flexible ones which we call muscles. A man's body, in place of being soft and supple, would be rigid and stiff as that of a tortoise.

If we look at the walking figure shown in Plate II. we see that the weight of the body is supported on the right foot, and that the heel of the left foot is raised, and that the left leg is just on the point of being swung forwards to be planted on the ground a step in front of the right foot. If our figure could actually move we should notice that, just as the advanced left foot was being planted on the ground the muscle-engines in the calf of the right leg would come into action and raise the right heel, thus propelling the weight of the body forwards.

There are three other muscle-engines fixed in the back of the leg, and hidden by the gastrocnemius and soleus, which are also set in motion as soon as the heel begins to rise. The long tendons or piston cords of these deep muscles of the leg (Plate II.) pass into the sole of the foot, where they are attached to the toes and other bony parts. No sooner has the heel begun to rise and the ankle to bend than these three auxiliary engines exert their force in steadying the foot and lifting the leg. On the outer side of the leg there is placed another set of muscles—the peroneal—which also helps in steadying the foot and leg (Plate II.). As the heel is raised and the front part of the foot is pressed on the ground a great strain falls on the bones of the foot, which are fitted together so as to form an arch. The arch is strained, and would yield or even collapse were it not sustained by the action of the leg muscles, and also by a regular battery of small muscles which are placed in the sole of the foot, and help to fill up the bend of its arch. Thus at the beginning of a step, just as the heel is being raised, there are more than a

score of muscle-engines being set in motion in the foot and leg, some of them big, others very small. Is it not wonderful, with so little trouble on our part, each and all of these engines are set to work just at the right instant of time, and act just at the right rate and with the right strength ?

We are watching how the heel is raised and the limb is swung forward as a step is taken. We notice that as the heel is raised a bending takes place at the knee and at the hip-joint (Plate II.), and then the limb begins to swing forward until the foot is again planted on the ground, the heel coming in contact with it before the toes. During that swing every one of the fifty-four muscular engines, which are placed within the moving limb, come into action, some for a short spell and others for a longer, but in point of action all are timed exactly. How wonderful the machinery must be which controls all of these engines we can best realise by remembering that, in walking at the rate of four miles an hour, only half a second elapses from the time the heel is raised until the limb has swung forward and the foot is again planted on the ground. Yet in that half second fifty-four engines have been started and stopped, speeded up and slowed down a countless number of times.

It is not necessary for us to go fully into the muscles or engines concerned in swinging the limb forward ; the muscles of the buttock which act on the hip-joint and those of the thigh—the hamstrings and extensors of the knee can be seen in the moving figure drawn in Plate II. But I should like to speak of one group of muscles which is called into action at the end of the forward swing just as the heel has reached the ground and the front part of the foot has been firmly planted there. It is then that the muscles which lie in front of the leg (Plate II.) and whose tendons may be felt passing in front of the ankle to be attached on the back of the foot and to the toes, come into action. They prevent the front part of the foot from going down with a jerk. They act as "pull" engines, but "pull" engines of a curious kind. When a

muscle passes into action it becomes shorter and thicker and thus moves the particular lever or crank-pin to which it is attached. But these muscles in front of the leg let the front part of the foot sink gently on to the ground by passing into action and yet gradually getting longer and longer, thus supporting the front part of the foot as it settles down. Herein we see that the engines of the human body can not only pull upon and bend levers but they can also, by a sort of reversed action, serve as guy-ropes or brakes and thus allow the levers to sink gently to a position of rest. Every boy and girl must have noticed the painful feeling which is felt in the front of the legs on descending a long and steep hill. The front part of the foot has to be supported in each step for a much longer time when a hill path slopes rapidly downwards in front of us ; hence the muscles or engines which let the toes down become very tired and cry out with pain. Wherein they are very different from metal engines. There is another way of making the muscles very tired and that is by wearing very high heels as some ladies did at the time I gave these Christmas Lectures. The heels being very high, they come into contact with the ground too soon and the muscles in front of the leg become very tired because they have extra work to do in letting the toes down. But here again muscular engines are better than metal ones ; they soon become strong enough to bear their extra burden and no longer feel painful. Over-work never makes a metal engine stronger ; overwork wears them out.

We are so accustomed to the way in which the human machine runs that it never strikes us as being at all uncommon or droll. But if a horse could tell us what he thought of our manner of walking, I am sure he would say it was the drollest way of getting forward in all the world, so different from the sensible way adopted by all ordinary four-footed beasts. When we take a step, one leg rests or supports the body while the other swings forward. In the next step the swinging leg becomes the resting limb and the resting one then swings forward.

We have been speaking so far only of the swinging limb; we have seen that during that movement all its muscle-engines—some fifty-four in number—are set in motion, but so far we have said nothing of what the corresponding engines in the stationary or supporting limb were doing when the swinging limb was passing forward. As a matter of fact they were thrown into action and were performing a very skilful acrobatic feat. If I were to poise a man's body on the end of a billiard cue and maintain it balanced so for some time, you would look upon me as a wonderful acrobat. And yet if the walking figure of the man shown in Plates I. and II. be examined, it will be seen that a feat of this kind is being carried out with every step. In that figure the right leg is shown as the stationary or supporting member; the left as the one which swings forward. The whole weight of the man's body is supported on the round, slippery, and ball-shaped head of the right thigh bone; it is balanced there by all the muscles which surround the hip-joint, some fifteen in number, being set into motion and working against each other. The socket of the hip bone or pelvis in which the head of the thigh bone is pivoted is equally smooth and slippery. As the swinging limb is flung forward under its proper engines, the centre of gravity of the body has to be poised vertically over the head of the thigh bone of the stationary limb and kept thus balanced by muscles which pass up from the thigh bone to act on the hip bone or pelvis. The hip bone serves as the crank on which the balancing muscle-engines act. The least bit the body sways off the plumb, this way or that, then at that moment the right muscles are set in more vigorous action to meet the emergency and bring the body back to the straight. All the time, too, that the free limb is swinging forward, the centre of gravity of the body is also being advanced, hence the balancing muscles of the stationary limb have to meet this change by varying the rate of their action.

We have been thinking only about the muscles of the stationary limb which balance the trunk on the top of the

thigh bone. It is quite evident, however, when we come to watch what really happens as we walk, that the foot of the stationary limb is being all the time adjusted to the ground, the arch of the foot is being supported, the ankle-joint is being steadied, by the ever-alert action of the muscles and tendons which are placed in the leg and foot. They also are in action all the time. The knee-joint, too, has to be kept under control and supported. Indeed all the muscles of the stationary limb are set in motion and kept at a necessary pitch of work during the period that the other limb is swinging forwards. There is one great muscle-engine in front of the thigh—the quadriceps or extensor of the knee—which is not thrown into action in the stationary limb. One has only to take hold of the knee-cap to make certain of this ; it will be found not to be fixed but to be quite loose. Thus in taking only a single step almost every one of the muscles or engines of the lower limbs—108 in number—are set going, not all at once but in a definite and wonderfully regulated order.

CHAPTER III

HOW THE BACKBONE IS BALANCED AS WE SIT, STAND, OR WALK, AND SOME POINTS OF DIFFERENCE BETWEEN THE MOTOR CYCLE AND HUMAN BODY

In the last chapter we have been speaking of the engines which move the legs in walking ; we should make a great mistake, however, if we thought that only the muscles of the lower limbs were at work when we walk. There is one other and very important part of the body which has at the same time to be kept upright and balanced, and that is the backbone or spine. If we have had to walk a long way, especially if the day has been close and hot and the road hard and dusty, we are glad to sit down, for that rests the tired muscles of our legs and thighs and gives them time to regain strength. But it is not enough merely to sit down ; to feel really comfortable we must bend forwards and rest our bodies against our knees, or recline backwards against a fence or tree trunk ; or if very tired we throw ourselves down on the sward, and that position brings a feeling of relief. Clearly then when we walk more muscles than those of the limbs become worn out ; those of the back also become tired and need a rest.

It is not only when we stand or walk that the muscles of the back have to be set to work. Every boy and girl knows how tiring it is to sit bolt upright in school ; presently comes the wish to lean backwards against something, or to bend forwards over the desk and rest the head on a hand, or to twist the body round a little ; all of these plans seem to bring us greater ease. We want to

know the reason why it is so very tiring to sit bolt upright, and to do that we must know something of the wonderful machinery of the backbone or spine. We shall see that it is provided with scores of levers, and each lever has two or more little living engines which move and work it.

In the walking skeleton (Plate I.) the backbone is seen to rest on the pelvis ; above, it has the skull mounted on it ; the ribs are also attached to it, twelve on each side. In a skeleton, the backbone appears to keep upright without the help of muscles, but that is only because a stiff iron rod has been thrust along it, thus fixing together the twenty-four blocks or vertebræ, which are built up on it, one above another. In life each segment or vertebra is free to move, and hence has to be balanced by means of muscles. That is why our bodies can be bent backwards and forwards or from side to side or twisted ; in old age the vertebræ often become joined together, and then we walk stiffly and move with great difficulty.

We can easily imagine how the backbone or spinal column is made up if we take from a child's play-box twenty-four wooden cubes and build them up in a single pile or column. We must place the larger blocks at the foot of the column and the smaller ones at the top, but even then we shall have a difficulty in preventing the pile from toppling over. To a column thus built up we must add something more if it is to resemble the spine of our back. It has to be buffered. Railway engineers soon discovered that when they joined railway coaches together to form trains they bumped so hard against each other when the engine slowed down or stopped that the passengers who rode in those primitive trains were badly shaken. Hence they invented buffers which take up the shock when railway coaches are forced against each other, and thus passengers are able to ride in comfort. That is what Nature did to our spines. She set between each pair of blocks or vertebræ which make up the train of the spine a very wonderful kind of buffer, which not only absorbs shocks but binds the vertebræ so stoutly together that

they are never pulled apart however severe the accident. The buffer or disc set between the vertebræ is made like a water-cushion. Its centre is pulpy and springy, while the surrounding cover, which also binds the vertebræ together, is very strong (fig. 3, B). We all know how rough it is to ride in a farm cart, and how smoothly a journey goes in a good motor car; the difference is due to the fact that the farm cart has no springs or buffers. If it were not for the intervertebral disc our journey through life would be like riding in a farm cart. It is because of these discs or buffers that we do not feel a jar with each step, or do a damage to our bodies when we take a high jump. The human machine, particularly the backbone, has been so skilfully cushioned or buffered that we can walk, run, or jump on the hardest and roughest roads, and yet its most delicate parts suffer neither discomfort nor damage.

Now, when we walk, these twenty-four blocks or vertebræ have to be kept balanced, one upon the other. During each step the poise of the body is being altered, and the column of vertebræ would fall to one side or the other if we had no means of keeping them rightly poised. For that purpose a very great number of muscular engines are provided which can turn the backbone in this direction or in that, just as is required to keep our bodies upright. In order that the vertebræ may be moved with ease and precision they have been furnished with levers or processes, and these the muscular engines use as crank-pins. Each vertebra has a hinder lever or *spinous* process (fig. 3) so that when the spinal column threatens to fall forwards muscles attached to these processes are able to bring it back into the erect position. By means of this lever a vertebra can be partly turned or twisted. The column might tend to fall to the right or to the left side; each vertebra is accordingly provided with a right and left lever or *transverse* process; each of these side levers is moved by special muscles. Or the tendency might be for the spine to fall backwards; this danger is provided against by very long levers which are called ribs. We

shall see that these levers form part of a great air-pump—the chest or thorax (Plate I.). Their chief use is to enlarge the thorax and draw breath into the lungs, but we must not forget that they are also the most powerful levers of the spine; all the muscles which are attached to them can and do help in keeping the spine erect. Thus we see that the spine is provided with levers and muscles to prevent it from swaying backwards, forwards, to the right or to the left. We can not only bend our bodies in all of these directions, but we have also the power of twisting or partly turning the vertebræ on each other, so that we can look over the right shoulder or over the left.

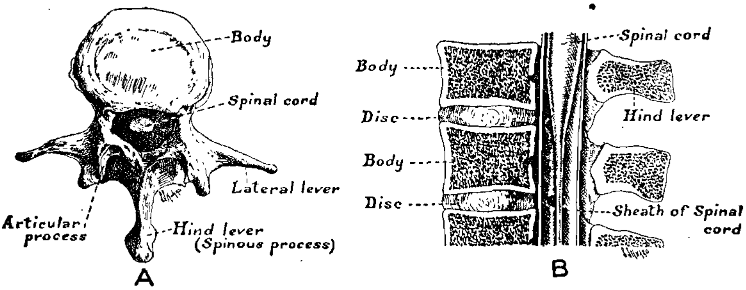


FIG. 3.—Plan of vertebræ in the lower or lumbar part of the spinal column. A, A lumbar vertebra looked at from above to show its levers. B, Three lumbar vertebræ showing the discs between them which act as buffers.

It is clear, then, that there are also muscles which can act on the levers of the vertebræ and produce a twisting movement. The elaborate machinery needed for balancing the vertebræ on each other and for keeping the spine erect is now becoming evident to us. We have seen that there are 24 vertebræ poised one above another; each has not less than 3 levers to be worked, some of them 5; each of the 24 vertebræ has at least 6 effective engines working on it, bending it to the right, left, forwards, backwards, or twisting it, as occasion requires. With 24 vertebræ and 6 muscles supplied to each, we have a total of 144—a gross of engines, which we employ to balance the spine in every step we take. They are set in motion, speeded up, and slowed down with every step.

Now we begin to understand that the human body is a very intricate machine, and the more we know about it the more we marvel that every little child, as it learns to walk, is also able to master the machinery of its backbone.

We have not yet finished with all the engines which are set in motion when we walk. We have counted 108 of them in the lower limbs and 144 in the back. But we have not thought of the head, which is balanced on the top vertebra or *atlas*. Twenty muscles are required for this purpose. Then there are the shoulders ; if you look at the skeleton you will find that the shoulder-blades (Plate I.) are fastened on by pins or wires, otherwise they would fall off. In the living body they are kept up by muscles which are active and busy so long as we are walking, standing, or sitting. They, too, will become tired in time and then the shoulders ache. Besides, there are also the muscles of the arms ; when we are walking we find that if the arms are swung we feel easier and better balanced.

We now begin to see why we are tired at the end of a long journey on foot. With every step—every half second—some three hundred engines have been started, regulated and stopped, and each has done its allotted task in helping the body forward. But why is it that, when we have stood still at attention or sat bolt upright for half an hour, we feel more tired than after a long journey ? That is because, if we are walking, running, jumping, or turning about, our muscles work alternately ; when one is doing a turn, another is having a spell off. But if we stand at attention or sit bolt upright there is no alternation of work and rest ; the muscular engines are kept steadily at work all the time. The drill sergeant knows how soon men become tired if they have to stand at attention ; he relieves them by giving the order "stand at ease," because when we stand easy we make certain muscles keep the body upright and allow the others to rest ; then we change our position, so that the rested muscles have in their turn to do the work of keeping the body upright. It is good for boys and girls to have to sit upright for

a short time if they may sit at ease after each spell. Engineers tell us that we have to know a great deal before we can manage a motor engine rightly, and when you think about the human machine, I am sure you will agree with me that it needs quite as much care and understanding for its proper management as any engine which man has invented.

I have spent such a long time in counting over the engines which are set working when the human machine is made to walk or run, that there is danger of our forgetting what I really am trying to prove to you. I want to show that we can learn a great deal by comparing together the motor cycle and the human body. Both have the power of moving; both are fitted out with engines which act on the levers and compel the machine to move forwards, backwards, or turn about. I have to admit that the motor cycle is the more simple machine—it has only one engine to drive it forward, whereas the human machine needs about three hundred of them. But we must also admit that if we were to collect all of these engines from the body of a strong, fully grown man they would not weigh more than 60 lbs., the same weight as the single engine which is usually fitted to a motor cycle. It is true that the single engine can make the motor cycle travel four or five times the speed that the fastest sprinter can attain, although his body is fitted out with hundreds of motor engines. The motor cycle, too, can haul a load which will tax the strength of twenty robust navvies. The engine of the motor cycle has not only a greater brute strength, but it never becomes really tired or needs a rest. Why, then, was the human body not fitted with a single engine and set on wheels? As a matter of fact the human body is fitted out on a wheel—a wheel of a peculiar kind. It is a wheel with only two spokes, with a hub at the hip-joint and felloes or rim at the feet. But because these spokes are movable, first one swinging forwards then the other, they are able to do the work of the twelve spokes which are fixed together in a circle so that they come in contact with the ground one after the other. A

wheel is really a great number of legs and feet set together so as to move round in a circle. The wheel of a motor cycle — with its multitude of spokes — is a wonderful invention, and the wheel of the human body with two movable spokes which can serve the same purpose as twenty fixed ones is not only more wonderful but more useful. Human beings go over all kinds of country, jump ditches, get over hedges, climb trees, go upstairs, and do a multitude of things which a motor cycle, although it can travel so fast, cannot do. Indeed man had to make smooth and level roads before wheeled vehicles could be used at all. Instead of using a single strong engine as in the motor cycle, the human machine has been provided with hundreds of them, placed all over the body, where they work the various levers of the limbs and trunk.

CHAPTER IV

ARE OUR MUSCLES REALLY INTERNAL-COMBUSTION ENGINES?

We must now look more closely into the machinery of a muscular engine. In the last two chapters we have been merely counting over the number of these engines in the human body, and noting how they set the bones in motion when we walk. The engines set the limbs moving, just in the same way as the internal-combustion engine of a motor cycle makes the hind wheel go spinning round. The muscular engine we are to choose for our present purpose is one which everybody can study, namely, the biceps muscle, placed in front of the right arm. It is not difficult to feel it in action; you have only to clasp the part of the arm in which it lies with the left hand, and then, as the elbow is bent and the right hand rises towards the face, it is felt to become thicker, harder, and shorter. That is what happens to every muscular engine when it is set in motion. In the drawing shown in Plate II. the biceps is seen stretched out and lying side by side with other muscular engines, but in fig. 4 all of these have been taken away, so that we may devote our attention to the biceps alone. We must first look at the manner in which it is fixed to the base or fulcrum from which it exerts its power. We see that it is fixed by two heads—hence its name. Both of these are attached to the shoulder-blade or scapula, one just above the shoulder-joint, the other to a finger-like process of bone called the coracoid. Its tendon or piston cord ends in the forearm, being fixed mainly to the radius, one of the two bones in the fore-

arm. The forearm is the lever on which it acts; whenever it is set in motion it lifts up the forearm and hand and thus bends the elbow. But it can also be made to rotate the radius so that the palm of the hand is turned upwards.

In the engine of the motor cycle (fig. 1, p. 10) we saw that there was a pipe—the inlet pipe—which conveyed to the cylinder the explosive mixture made up of fine particles of petrol diffused through eight or nine

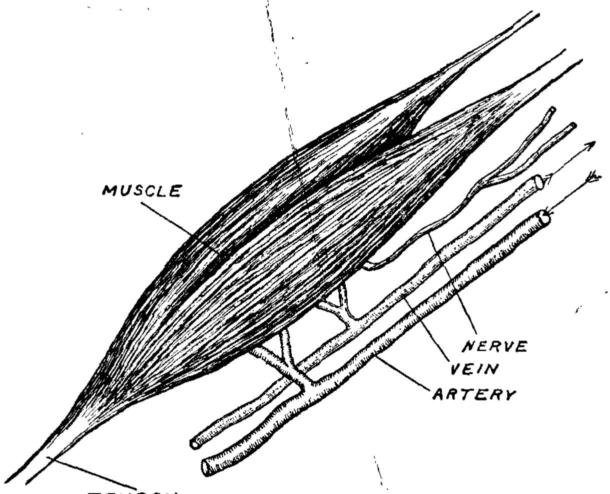


FIG. 4.—A drawing of the biceps of the right arm showing its tendon, its vessels, and its nerve.

times the same weight of air; then we saw another pipe—the exhaust pipe—which carried away from the cylinder the gases formed when the charge was exploded. Now the muscular engine has corresponding pipes (fig. 4); there is not one pipe but several which enter the biceps muscle, only we name them not pipes but arteries, and they convey to the muscle not petrolised air but red arterialised blood. Then there are pipes which issue from the muscle and carry away from it, not waste gases but dark venous blood. Only we do not call these vessels exhaust pipes, but veins. Then, too, we saw that a wire ended in the

combustion chamber of the cylinder and carried an electric current which fired the explosive mixture and set the engine in motion. A cable of most peculiar "wires" also enters the muscle ; we call the cable a nerve, and the current or messages which it conveys to the engine are not electric but of a different kind, yet they serve the same purpose : they set the muscle in motion.

If we look more closely we shall find that not only have the engines of the motor cycle and of the human machine pipes of a corresponding kind, but that through these pipes there passes a circulation which serves a similar purpose. Petrolised air is pumped through the circulatory system of the engine of the motor cycle ; arterialised blood is pumped through the corresponding system of the muscular engines of the human machine. But the system of pumping employed in muscular engines is by far the superior. We have seen that in the 4-cycle internal-combustion engine only one stroke in four is really effective ; the other three are spent on pumping or circulating the explosive mixture. The first stroke we saw drew in petrolised air and thus charged the cylinder with an explosive mixture ; the second compressed the mixture into the combustion chamber ; the third stroke, which is the only effective or driving one, is caused by the explosion ; the fourth one sweeps out the waste gases through the exhaust (figs. 2A–2D). Thus three strokes out of every four are used to keep up the circulation of petrolised air through the engine. So far as driving power is concerned these three strokes are lost or wasted. Engineers are trying hard to make each stroke of the engine an effective or driving one. Sir Dugald Clerk has succeeded in getting rid of two of them. He managed to do this in a very simple manner. He attached a pump to the engine in such a way that it forced a charge of petrolised air into the combustion chamber just when the piston had swept all the waste gases through the exhaust and was ready to begin a new stroke. Thus the first or suction stroke and the second or compression stroke became unnecessary ; in this way two strokes were saved.

Many millions of years before man had thought about motor cycles, Nature had invented a method of making each stroke of the muscular engine effective. She did this by means of a wonderfully contrived pump called the heart. It is this pump which maintains a constant circulation through the muscular engine we are now considering—the biceps. Through the arteries it pumps into the muscle blood which contains both fuel and air—an "explosive mixture"; the blood returns by the veins laden with waste products. The biceps does not look at all like the engine of a motor cycle, but when we look beneath the surface we see that they have corresponding parts.

We now come to a question which is very difficult to answer clearly. Does the biceps of your arm, when it contracts and bends the elbow, really act as an internal-combustion engine? Long ago Faraday delighted boys and girls in the Royal Institution at Christmas time by showing them that all the secrets of combustion can be studied in a lighted candle—the hydrogen and carbon elements which, locked up in the tallow or wax of a candle, begin to unite with the oxygen of the air when a lighted match is applied to its wick. As every boy knows, water and carbon dioxide are formed in the process of burning or combustion, and heat is also given off or generated. The same thing occurs in the combustion chamber of an engine when an electric spark fires the mixture of petrol and air. The hydrogen and carbon elements of the petrol instantly unite with the oxygen of the air, causing an explosion. The explosion spends its force in thrusting down the piston and thus driving the engine; heat is generated, water and carbon dioxide are produced—all being the results of "internal" combustion. Now, if we can show, when a muscular engine is set in motion, that carbon dioxide and water are formed and that heat is given off, then we should have grounds for thinking that there is another point of likeness between a motor cycle and a human body—both are fitted out with internal-combustion engines.

We must first find out if our muscles are supplied with an explosive mixture. We can see that the blood which is being pumped into them through the arteries is bright red ; that is because the millions of microscopic discs or red corpuscles, which float in the fluid or plasma of the blood, are charged with minute loads of oxygen. In the plasma there is a hydrocarbon compound—a kind of sugar—which serves as fuel or petrol for the muscle. Thus we find that the blood pumped into a muscle through its arteries is laden with the ingredients of an explosive mixture. The blood leaving by its veins has lost its bright colour and is laden with waste products, especially carbon dioxide. The harder a muscle is made to work the quicker becomes the current of blood which passes through it, and the greater is the output of products of combustion. Heat also is generated. All *these are signs that muscles act as internal-combustion* engines, just as the engine of a motor cycle. But there is one important difference. In the motor cycle engine carbon dioxide is produced at the instant when the explosion occurs and the piston gives its driving stroke. This is not the case in the muscular engine. Sir Walter Fletcher and Sir F. G. Hopkins found out that the carbon dioxide (CO_2) is not thrown off at the moment of contraction but afterwards. A process of combustion or oxidation therefore does take place in the muscular engine, only it does not occur as an explosion but in a slower and better regulated way. Yet it is clear that the muscle is an internal-combustion engine of a peculiar sort, very different and much superior to any kind which man has yet invented. Apparently the muscular engine builds up the materials supplied to it into a particular kind of fuel, which it can store and use when needed.[1]

There is another point in which a muscular engine like the biceps is greatly superior to mechanical engines. With the biceps we can give what length of stroke we will. We can make it move the forearm with a stroke

[1] See Appendix B, where an account is given of more recent advances in our knowledge of combustion in active muscles, p. 276.

which is only a twentieth of an inch in length, or we can make it bend the elbow through its full range from complete extension to complete flexion. We can make it work the forearm at any point of its range of movement, quickly or slowly, gently or strongly, just as we please. It is true that engineers can alter the strength and rate of the stroke of a mechanical engine by opening or closing the throttle valve, thus regulating the amount of explosive mixture admitted ; but there is only one length of stroke—that to which the engine is set. Think for a moment what our case would be if the biceps had only one length of stroke. We should set it, I suppose, so that it could just reach the mouth in feeding. To make a delicate or short movement at the elbow would be impossible. We should have to bring the hand as far as the mouth or not at all. In the muscle-engine a method has been discovered of regulating the rate of combustion as well as length of stroke. Work is not performed by a series of unregulated explosions as in a motor engine, but by a regulated process of oxidation which we do not rightly understand as yet.

There is another difficulty which all who drive motor cycles or motor cars have to contend with. When driven very hard they may get overheated, and so damaged as to become unworkable. Engineers have striven to find out a perfect way of keeping the cylinder from becoming overheated. They have contrived methods of circulating cool water round it, or of causing draughts of air to blow upon it, and many other ways, but all of them are apt to fail. Then, in winter, there is another mischance which may happen to a motor engine. It may become so cold that the petrol will not vaporise properly —will not ignite and will not explode. Hence we notice that a careful driver, when the weather is cold, always throws a thick rug over the engine when his motor car has to stand still for some time. The engines fitted to aeroplanes, which are exposed to great cold when high flights are undertaken, are kept warm by means of a coat heated by electricity. Drivers not only know that

over-heating or over-cooling will stop their engines, but have also discovered that there is a certain temperature at which they go at their best. No one has discovered the means by which a metal engine can be kept at the right temperature, but Nature has ; she has fitted out muscular engines with a mechanism which keeps them constantly near the temperature best suited to bring out their working powers. That degree of heat is the temperature at which the living body is constantly maintained—about 98° Fahrenheit. Muscular engines never become overheated and rarely over-cooled. Indeed, athletes who run races, and men who box or fence, know very well that their muscles work best when they are a little overheated by active exercise.

We are now to examine this wonderful mechanism which regulates the heat of muscular engines, but before we do that I must make a confession. I have been speaking of the biceps muscle as if it were an engine with a single cylinder. Now, although the biceps acts as a single engine it is made up of myriads of cylinders. In the well-developed biceps of a working-man there are 600,000 of these microscopic engine cylinders. Although it is only medical students who dissect the human biceps muscle and examine it closely, yet every one is familiar with muscular engines because we live on them. We are all engine-eaters, unless we are vegetarians. We eat the engines which gave the power of movement to some self-complacent ox, sheep, or pig. Their red flesh or muscle, especially if it has been boiled, can be separated into very fine threads or bundles. To see the cylinders—or primitive fibres, as the anatomist names them—we must take from a boiled muscle one of these very small threads, and then tease it out under water with fine needles until the shreds are so minute that they can scarcely be seen with the naked eye. When such shreds are examined through a compound microscope they are seen to be made up of narrow soft cylinders, each of them being wrapped round by a transparent skin or covering. How small these cylinders are may be realised

by looking at the drawings given in fig. 5. There the fibres are drawn as if they were 10 millimetres wide ($\frac{2}{5}$ of an inch), but this is one hundred times wider than they actually are. If we were to enlarge a man who is 6 feet tall on the same scale we should have to make him 600 feet high! But although these cylinders are so narrow that they cannot be seen with the naked eye except when a number of them are joined together so as to form a thread or fibre, yet they may be 10 millimetres long or even 25 millimetres, which is equal to an inch. They lie

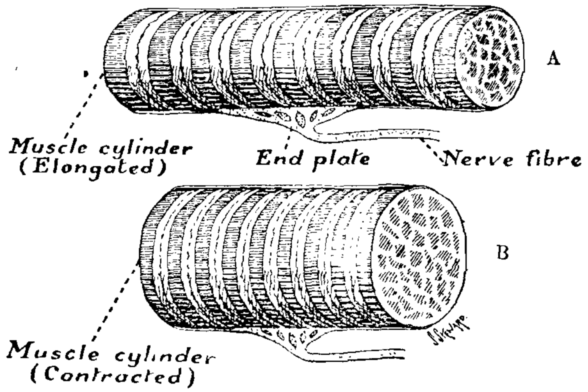


FIG. 5.—A, A primitive muscle fibre or cylinder in an uncontracted state; below, a nerve fibre is seen going to it and ending on a nerve plate. B, A cylinder in a state of contraction with its nerve fibre.

side by side in rows, and are joined together end to end like a string of sausages. At one extremity of a muscle the cylinders are joined to tough white fibres which fix them to the bone or station from which they exert their power. At the other extremity the cylinders are joined to strong white fibres which become collected together and form the piston cord or tendon of the muscle. All the cylinders of a muscle thus work on one piston.

Thus in a muscle like the biceps we have an engine made up of tens of thousands of microscopic cylinders. There are no combustion chambers in these cylinders for each is filled with a semifluid living substance. Yet in these cylinders combustion does certainly take place (see

Appendix B). Nor can we discover any rigid wall such as the cylinders of metal engines have, nor can we see any sign of structures which look like pistons. All that we can see is that each muscle-cylinder is made up of dark-looking discs separated from each other by clear spaces or discs. These alternate dark and clear discs are shown in fig. 5, where the upper diagram represents a cylinder at rest, the lower, one which is in a state of contraction or action. When the cylinder is contracting or working the discs come closer together; they become thinner and wider. When the millions of cylinders in the biceps are thrown into action at the same time, as they usually are, the whole muscle becomes wider, harder, and shorter; the piston cord is drawn up, and the forearm, the lever on which the muscle acts, is bent.

Now we must not forget that what we are really searching for is the mechanism which regulates the heat of muscular engines. We have just seen that a muscle, such as the biceps, is made up of thousands of microscopic cylinders, so that our problem is to find out how the heating of cylinders is managed. In fig. 6 three of these microscopic cylinders are drawn; between the cylinders are shown the minute kind of blood-vessels or pipes called capillaries; they are so narrow that the microscopic red blood corpuscles, each carrying its load of oxygen, can pass along only in single file; their walls are so thin that the fluid part of the blood, containing the kind of sugar which serves as fuel for muscular engines, can soak through and reach the cylinders. The cylinders are also greedy for oxygen and somehow manage to relieve the red blood corpuscles of their loads and send back in exchange the products of combustion—or, if you like, oxidation—especially CO_2. The blood is pumped into the capillaries, through very small arteries, by the heart; it is collected from the capillaries and carried away by veins. There is thus a constant circulation of blood round each muscle cylinder. The blood is kept at the same heat as the body; if the cylinders are above that temperature they will be cooled by the blood; if they

are below they will be warmed by it. This is only one of several ways in which temperature is regulated in muscles.

There is another structure which we must take into our consideration if we would find out every part of the machinery which is needed to regulate the temperature of muscular engines. We have seen that a cable of nerve fibres goes to every muscle; through the nerve fibres the will sends messages which set the muscles into motion, can make them contract less or more, or can

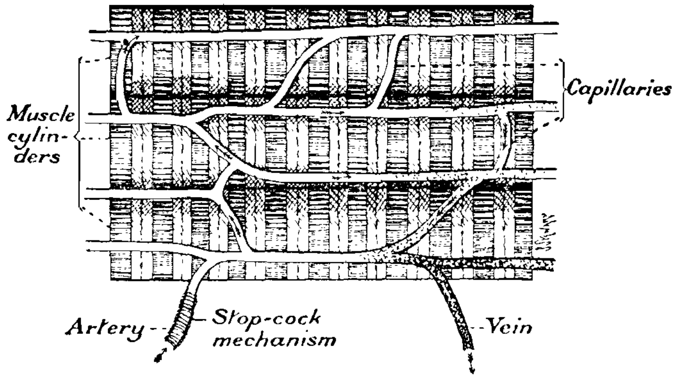


FIG. 6.—Showing the manner in which capillaries are arranged among muscle cylinders.

make them cease contracting. But we have not looked at the exact way in which the separate wires or fibres of the nerve cables end. The manner in which they reach the separate cylinders is shown in fig. 5; there a nerve fibre is seen entering its "end plate"; the end plate is applied closely to the muscle cylinder. A nerve message, when it reaches an end plate, gives rise to a contraction in the muscle cylinder, just as the electric current when it reaches the sparking plug of an internal-combustion engine gives rise to an effective stroke. The end plates seem to be a kind of sparking plug, only they can do more than any sparking plug which has been invented. Through them the nerve current or nerve messages

seem able to regulate the rate of combustion, just as a skilful driver can when he alters the throttle valve of his engine. We know very well that if these nerve paths are cut, then the cylinders are not only thrown out of work but become broken up; they "go to bits," as it were; they become as useless as an engine from which the sparking plug has been removed. Nay, more, these microscopic engine cylinders must not only be provided with nerves and end plates, but, to keep in good repair, they must be exercised often and well. Hence the need for regular exercises. No engine, except the muscular one, becomes better and stronger when it is given a full amount of work.

This chapter is becoming too long, so I must again ask the question which we originally set out to answer: Are the muscles of the human body really internal-combustion engines? Can they be compared to the engines of a motor cycle? In each we have found the circulation of a combustion mixture, in both heat is produced, in both there are structures which may be called sparking plugs, in both there are the usual waste products of combustion—water and carbon dioxide. The muscular engine, therefore, seems to be an internal-combustion engine of a peculiar kind. In the engine of the motor cycle the space within the cylinder is lengthened when an effective stroke is made, but in the muscular engine the opposite happens; the cylinder itself becomes shorter and wider. It is quite clear that Nature has invented a better kind of internal-combustion engine than man has yet thought of. We do not know its mechanism, but some day a boy, or perhaps it may be a girl, will be born who will discover this great secret of Nature.[1]

[1] As will be seen by a reference to Appendix B (p. 276), physiologists are rapidly discovering the manner in which combustion is carried out in muscular engines, and the kind of fuel which is burned in them.

CHAPTER V

MUSCLES ACT AS RECIPROCAL ENGINES, BUT IT TAKES YEARS TO LEARN HOW TO MANAGE THEM

We are all engine-drivers—drivers of muscular engines—but it is such a long time ago since we began to learn how to manage them that we have forgotten the difficulties which had to be passed through. There came a day when we managed to balance a small body and large head over a little pair of uncertain legs, and actually took three toddling steps from one pair of grown-up knees to another pair—to the surprise and delight of our beholders. They declared we had done a very wonderful thing ! and so we had ! We had succeeded, after being in this world little more than twelve short months, in setting into motion scores of engines, starting each of them just at the right instant, and in their right order, and each with the right degree of strength to carry us through our first short journey in life. There was again a day in which we gave another surprise. We actually spoke an unmistakable word ! We had at last discovered how to set in motion the muscles of the mouth, throat, and chest, so that they gave out that kind of sound we call speech. Although we use far fewer muscles in speaking than in walking, yet it was the set used in speech that was hardest to master. Afterwards came a time when we could actually run, jump and climb, put our clothes on and off, fasten and undo buttons, use a spoon, fork, and knife, and sit quite quietly at table, a truly difficult accomplishment. All the while we were doing these things we were really learning how to drive engines, to start them and stop them at different

times and in different orders; we were learning how to make them work in harmony and be obedient to our will. Some of us remember the very morning a pen was put in our hand and the struggle we had with the battery of engines which move the fingers until they could be combined so as to form a perfectly straight stroke or an evenly rounded nought. We thought then that it was only a matter of making the fingers move smoothly and easily. We did not understand that the wrist had to be steadied by a group of engines which are placed in the forearm before the hand can work with precision. Then the forearm had to be steadied or controlled by the muscles of the upper arm, the upper arm by muscles in the shoulder, and the shoulder had to be made firm by calling into action the whole battalion of engines which balance the backbone. Is it any wonder, then, seeing that a hundred engines and more are set going before we can handle a pen, that each of us writes our name in our own style? No matter how many John Smiths there may be, the cashier who pays money to them at the bank can tell at a glance the signature of each. Each one of us writes his own way, walks his own way, and speaks his own way, because in every one of these acts we have to set in motion and regulate such a great number of muscular engines that no man could learn to drive or time them in exactly the same way as his neighbour.

Is it not a fortunate thing that the greatest pleasures we have when we are young are the games and sports which stimulate us to obtain a perfect control over the muscular engines of our bodies? What boy does not dream that one day he may be chosen to play for his village, his school, his county, his university, or even his country, because he has become a master driver of the engines of his own body? That brilliant left-hand catch which we saw made on the cricket-field, the throw-in from mid-field which shattered the wicket, the perfectly timed stroke, are they not all of them displays of perfect engine driving? Then there are the accomplishments of life—attained by hours, days, and years of *practice*—of

learning how to control the fingers in playing and the voice in singing. The perfect singer or player is he or she who, having been born with a gift for music, has gained a control over the muscles of the voice and hand so completely that they they can be timed in their action to an infinitely small fraction of a second. In the expert artist the will has become a perfect engine-driver. Then there are the skilled pursuits of life—the expert use of the chisel, the hammer, the saw, the brush, the carving- and graving-tools—all the skilled arts and crafts in which proficient workmen take a pride. Some become masters of their engines more easily and more quickly than others, but all have to serve an apprenticeship in the great game of life—the game of setting our muscular engines to work in the right order, with the right strength and at exactly the right moment.

Our lives would have been so much simpler and easier if, like a motor cycle, we had been fitted out with only one engine! That would have been possible if we had been content to do only one thing in life—namely, to spin straight along a smooth road. That would not content anyone for long. We should want to eat and drink, sing and play, and do hundreds of other things; therefore we must have hundreds of muscular engines to do these different things. And having hundreds of engines introduces into our bodies a difficulty which I am now to try to explain. Our muscles have to act as reciprocal engines. I can make my meaning clear by taking an instance from the arm. In fig. 7 all the muscles have been stripped from the upper arm except two—the anterior brachial and triceps. For you must understand that muscular engines as well as railway engines are given names. The forearm is the lever or crank on which both of these muscles act; the brachial bends or flexes the elbow; the triceps straightens or extends it. Each has to give and take as the other takes or gives; they have to act as reciprocal or opposing engines. In fig. 8, which is set side by side with fig. 7, these two muscles have been taken away, and in their places have been fixed two internal-

combustion engines made on the same plan as that of a motor cycle. We need not stop to explain that we have substituted "push" engines for "pull" engines, and that they act in a reverse direction. If we now wish to unbend or extend the elbow we set the anterior engine at work, and it extends the elbow, thus pushing the forearm down. It will be observed that when the forearm is being unbent the piston of the triceps engine must move upwards

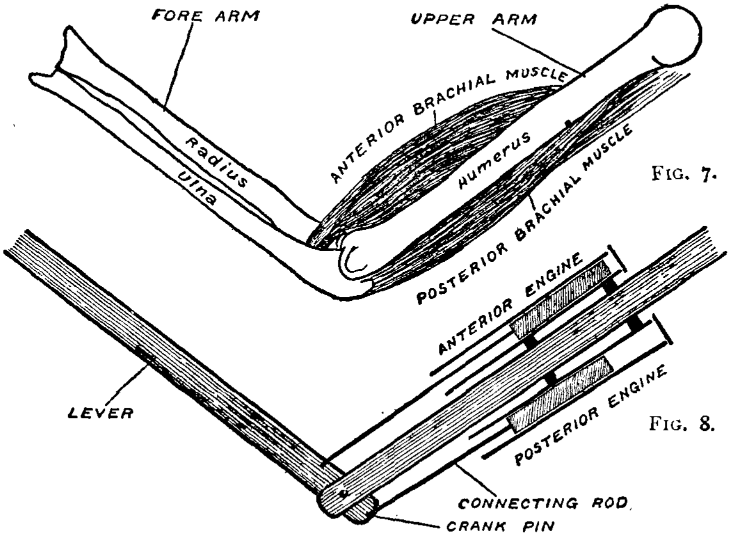


FIG. 7.

FIG. 8.

FIG. 7.—Showing the anterior brachial muscle which flexes the forearm, and the posterior brachial or triceps which extends it.

FIG. 8.—Showing the brachial and triceps muscles replaced by internal-combustion engines.

to a corresponding degree. Likewise, if we bend the elbow, by setting the triceps engine in motion, the piston of the biceps must move upwards to a corresponding degree. The one engine cannot move without a reverse action taking place in its opponent or antagonist. They have to work as reciprocal engines, and therefore their strokes must be perfectly timed so that when the piston of one is ascending that of the other must be descending. It is clearly necessary that the two pistons

must move in the closest harmony if effective work is to be done; at every instant they must be so exactly balanced that the hand is kept perfectly steady for every delicate act in which it is concerned. There must be no opposition or jarring at any point of a movement—however intricate that movement may be. The one engine must feel all the time exactly what its opponent is doing, so that it may make its action respond. Engines which work by explosions, as those of motor cycles do, could not be so harmoniously balanced as to do that. Only the exactly regulated slow-combustion muscular engines invented and elaborated by Nature are capable of acting as perfect reciprocating antagonists.

Now all the muscles of the body are set as opposing pairs, or antagonistic groups, and Nature had to find out a way of making them work in harmony. She has done it in this way. Mention has already been made of the nerve fibres, which go to the end plates or sparking-plugs of the muscle cylinders. Messages reaching the end-plates set the cylinders in motion and also regulate the rate of their contraction and combustion. Besides these ingoing nerve fibres there are also other or outgoing fibres, with which every muscle is supplied. These outgoing fibres begin in curious little structures set amongst the muscle cylinders and also amongst the fibres of the tendon or piston cord. They act as "receptors" or end organs for taking up nerve messages. When the muscle goes into action, be it ever so slightly, these receptors are squeezed or pressed upon, and automatically dispatch messages which speed along the nerve fibres to the spinal cord and brain. The messages reach a centre or exchange, which controls its fellow or opponent muscle. Thus, through a system of "nerve exchanges," opposing muscles learn the exact state of each other. When a muscle is contracting hard, messages are being dispatched from it which make its opponent or opponents yield at the right rate, and yet offer sufficient resistance to steady or balance the part that is being moved. That is why it is so hard to become a perfect engine-driver—the

difficulty of balancing the action of our muscles, for all of them have to act as perfectly adjusted reciprocal engines. No wonder it is difficult to become expert at games or at skilled work! We see, too, what a wonderful machine the human body is. When we take even a single step we set three hundred engines in motion, we set each going at the right instant, and from each of the three hundred messages are streaming into the brain and an equally great number are being dispatched outwards from automatic control centres.[1]

Perhaps I have extolled the merits of muscular engines quite enough already, although I have not exhausted all their wonders. They run so silently that they do not seem to make any noise at all, and yet if you apply your ear to the biceps when it is set in motion, or especially if you listen to it with a physician's stethoscope, you will find that a muscle is not altogether a noiseless engine. Nor do muscular engines throw out ill-smelling gases! Then they never really stop; even if they are not actually performing mechanical work their engines are still kept running free, with their clutches off; but the clutch slips in automatically when we want to set the human machine in motion. Moreover, they are so wonderfully geared that we can change the speed as often as we like and to what degree we choose. Muscular engines always have their "steam up" and are ready to start work at an instant's notice. At the time these lectures were being given the ships of the British Fleet, which were lying in harbour, had to keep their furnaces alight day and night and their steam up, because no one knew the hour or minute they might have to sail. In order that the fleet might be ready on an instant to protect the life of Britain, endless tons of coal and oil had to be burned—wasted. The ideal engine would be one that completely stopped when not wanted, and yet was ready for action in the hundredth fraction of the time taken to twitch an eyelash. Muscular engines must often work quite as quickly as that to save the life of the human body. But even Nature has not invented so perfect an engine. Muscular engines have

[1] See Appendix C, p. 287.

always to have their "steam up"; their engines must continually be kept running free and using fuel when they are not actually in use. They are therefore always burning fuel, and are thus wasteful and expensive—if we do not use them. Some of them we shall see are always at work, minute after minute, so long as life lasts.

The first question an engineer asks about any new kind of engine is: What is the standard of its efficiency? The engine he is in search of is one which will turn every particle of heat or energy contained in oil or coal into effective work. He dreams of inventing an engine which will have a standard of efficiency of 100 per cent. So far he has not succeeded in making one which will turn more than one-fifth (20 per cent.) of the energy of fuel into effective work; the other four-fifths (80 per cent.) goes up the chimney or is wasted in some other way. Now in this respect the muscular engine, although it has to keep running whether in use or not, is quite good even from an engineer's point of view. Its standard of efficiency is about 25 per cent. It is able to turn one-fourth of its fuel into effective work.[1]

There is one very important difference between an engine constructed of metals and one made out of living flesh which I have scarcely mentioned, and it is a very important difference. The metal engine can be made to work for days or even for weeks at a stretch, whereas the muscular engine can only work well for a limited number of hours. Why should a muscle become tired? It is supplied through the blood, as we have already seen, with all the elements needed to form a combustible mixture, but before these elements are suitable for the peculiar kind of combustion which goes on in a muscular engine, they have to be worked up or compounded in the intermolecular spaces of the muscle cylinders. At present we suppose that, when a muscle has been working for

[1] For methods of estimating the efficiency of muscular work the reader is referred to Prof. J. S. Macdonald's paper in *Proc. Roy. Soc.*, 1917, Series B, vol. lxxxix. p. 394, and Dr M. Greenwood's paper, *Proc. Roy. Soc.*, 1918, Series B, vol. xc. p. 199. See also Appendix B.

some hours, the available store of fuel is used up, and then if pushed to do more it has to fall back on the fuel of its own substance—to use its decks for fuel, as it were. Hence rest is absolutely necessary for muscular engines to give them leisure to restore the supply of material which they change into work—in other words, to fill their bunkers.[1]

I have tried to make clear the marvels of the machine which every one of us has to drive. It is a machine which works so easily and so well, especially when we are young, that we think it needs no care or study, and that not even rough usage will damage it. Every night sweet sleep comes when those wonderful muscular engines of ours mend themselves and prepare for the morrow. There is no need for us to spend laborious hours overhauling them, seeing to their bearings, nuts, and fittings. They do their own repairs. And yet no one can make a greater mistake in life than to suppose that these engines may be neglected with impunity. There is one law which cannot be broken without our being sentenced or punished. This is the law of exercise ; the law that disuse and abuse will ruin any and every muscular engine beyond repair. If a muscle is neglected, if it is not used regularly, it first becomes weak, then it begins to waste, and ultimately it will become useless. Every one of them should be exercised moderately and daily. In the great game of life much of our happiness and our success depends on the treatment we meet out to our muscular engines.

[1] The reason why muscles become tired is discussed in Appendix B. It has been found that they become more and more fatigued as lactic acid accumulates in and round their cylinders. When lactic acid collects to an amount which represents $\frac{1}{300}$th of the total substance of a muscle, that muscle is completely exhausted and cannot contract. Nevertheless, under certain circumstances, muscles may use up their own substance.

CHAPTER VI

THE BONES OF OUR BODY ARE LIVING LEVERS. THE SKULL, BESIDES CONTAINING THE BRAIN, SERVES AS A LEVER OF THE FIRST ORDER

In all the foregoing chapters we have been considering only the muscular engines of the human machine, counting them over and comparing their construction and their mechanism with those of the internal-combustion engine of a motor cycle. But of the levers or crank-pins through which muscular engines exert their power we have said nothing hitherto. Nor shall we get any help by now spending time on the levers of a motor cycle. We have already confessed that they are arranged in a way which is quite different from that which we find in the human machine (page 14). In the motor cycle all the levers are of that complex kind which are called wheels, and the joints at which these levers work are also circular, for the joints of a motor cycle are the surfaces between the axle and the bushes which have to be kept constantly oiled. No, we freely admit that the systems of levers in the human machine are quite unlike those of a motor cycle. They are more simple, and it is easy to find in our bodies examples of all the three orders of levers. The joints at which bony levers meet and move on each other are very different from those we find in motor cycles. Indeed, I must confess they are not nearly so simple. And, lastly, I must not forget to mention another difference. These levers we are going to study are living—at least, are so densely inhabited by myriads of minute bone builders that we must speak of them as living. I want

to lay emphasis on that fact because I did not insist enough on the living nature of muscular engines.

We are all well acquainted with levers. We apply them every day. A box arrives with its lid nailed down; we take a chisel, use it as a lever, prise the lid open and see no marvel in what we have done (fig. 9). And yet we thereby did with ease what would have been impossible for us even if we had put out the whole of our unaided strength. The use of levers is an old discovery; more than 1500 years before Christ, Englishmen, living on Salisbury Plain, applied the invention

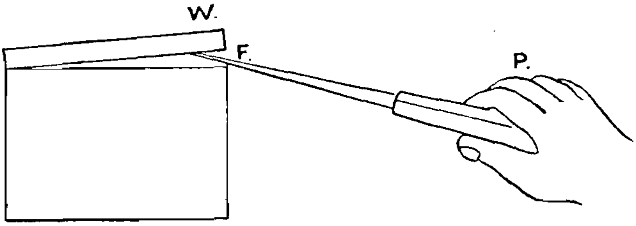


FIG. 9.—Showing a chisel 10 inches long used as a lever of the first order.

when they raised the great stones at Stonehenge and at Avebury; more than 2000 years earlier still, Egyptians employed it in raising the pyramids. Even at that time men had made great progress; they were already reaping the rewards of discoveries and inventions. But none, I am sure, surprised them more than the discovery of the lever; by its use one man could exert the strength of a hundred men. They soon observed that levers could be used in three different ways. The instance already given, the prising open of a lid by using a chisel as a lever, is an example of one way (fig. 9); it is then used as a lever of the first order. Now in the first order, one end of the lever is applied to the point of resistance, which in the case just mentioned was the lid of the box. At the other end we apply our strength, force, or power. The edge of the box, against which the chisel is worked, serves as a fulcrum and lies between the handle where the power is applied and the bevelled edge which moves the resistance

or weight. A pair of ordinary weighing scales also exemplifies the first order of levers. The knife edge on which the beam is balanced serves as a fulcrum ; it is placed exactly in the middle of the beam, which we shall suppose to be 10 inches long. If we place a 1-lb. weight in one scale to represent the resistance to be overcome, the weight will be lifted the moment that a pound of sugar has been placed in the opposite scale—the sugar thus representing the power. If, however, we move the knife-edge or fulcrum so that it is only 1 inch from the sugar end of the beam and 9 inches from the weight end, then we find that we have to pour in 9 lb. of sugar to equalise the 1-lb. weight. The chisel used in prising open the box lid was 10 inches long, it was pushed under the lid for a distance of 1 inch, leaving 9 inches for use as a power lever By using a lever in this way we increased our strength ninefold. The longer we make the power arm, the nearer we push the fulcrum towards the weight or resistance end, the greater becomes our power. This we shall find is a discovery which Nature made use of many millions of years ago in fashioning the body of man and of beast. When we apply our force to the long end of a lever we increase our power. We may also apply it, as Nature has done in our bodies, for another purpose. We have just noted that if the weight end of the beam of a pair of scales is nine times the length of the sugar end, that a 1-lb. weight will counterpoise 9 lb. of sugar. We also see that the weight scale moves at nine times the speed of the sugar scale. Now it often happens that Nature wants to increase not the power but the speed with which a load is lifted. In that case the "sugar scale" is placed at the long end of the beam and the "weight scale" at the short end ; it then takes a 9-lb. weight to raise a single pound of sugar, but the sugar scale moves with nine times the speed of the weight scale. Nature often sacrifices power to obtain speed. The arm is used as a lever of this kind when a cricket ball is thrown.

Nothing could look less like a pair of scales than a man's head or skull, and yet when we watch how it is

poised and the manner in which it is moved, we find that it, too, acts as a lever of the first order. The fulcrum on which it moves is the atlas—the first vertebra of the spine (fig. 10). When a man stands quite erect, with the head well thrown back, the ear passages are almost directly over the fulcrum. It will be convenient to call that part of the head which is behind the ear passages the *post-fulcral*, and the part which is in front the *pre-fulcral.*

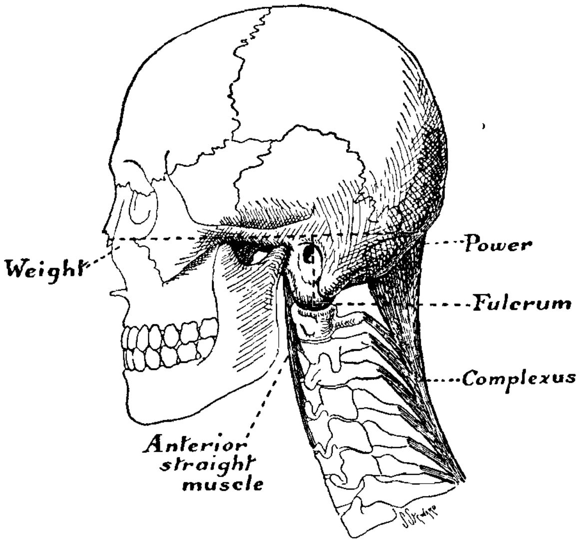


FIG. 10.—The skull as a lever of the first order.

Now the face is attached to the pre-fulcral part of the lever and represents the weight or load to be moved, while the muscles of the neck, which represent the power, are yoked to the post-fulcral end of the lever. The hinder part of the head serves as a crank-pin for seven pairs of neck muscles, but in fig. 10 only the chief pair is drawn, known as the *complex* muscles. When this pair is set in action the post-fulcral end of the head lever is tilted downwards, while the pre-fulcral end, on which the face is set, is turned upwards.

The complex muscles thus tilt the head backwards and

the face upwards, but where are the muscles which serve as their opponents or antagonists and reverse the movement? In a previous chapter it has been shown that every muscle has to work against an opponent or antagonist muscle. Here we seem to come across a defect in the human machine, for the *greater straight* muscles in the front of the neck, which serve as opposing muscles, are not only much smaller but are at a further disadvantage by being yoked to the pre-fulcral end of the lever, very close to the cup on which the head rocks. However, if the *greater straight* muscles lose power by working on a very short lever, they gain in speed; we set them quickly and easily into action when we give a nod of recognition. All the strength or power is yoked to the post-fulcral end of the head; the pre-fulcral end of its lever is poorly guarded. Japanese wrestlers know this fact very well, and seek to gain victory by pressing up the poorly guarded pre-fulcral lever of the head, thus producing a deadly lock at the fulcral joint. Indeed, it will be found that those who use the jiu-jitsu method of fighting have discovered a great deal about the construction and weaknesses of the levers of the human body.

To merely poise the head on the atlas may seem to you as easy a matter as balancing the beam of a pair of scales on an upright support. I am now going to show that a great number of difficulties had to be overcome before our heads could be safely poised on our necks. The head had to be balanced in such a way that through the pivot or joint on which it rests a safe passageway could be secured for one of the most delicate and most important of all the parts or structures of the human machine. We have never found a good English name for this structure, so we use its clumsy Latin one—*Medulla oblongata*—or medulla for short. In the medulla are placed offices or centres which regulate the vital operations carried on by the heart and by the lungs. It has also to serve as a passageway for thousands of delicate gossamer-like nerve fibres passing from the brain,

which fills the whole chamber of the skull, to the spinal cord situated in the canal of the backbone. By means of these delicate fibres the brain dispatches messages which control the muscular engines of the limbs and trunk. Through it, too, ascend countless fibres along which messages pass from the limbs and trunk to the brain. In creating a movable joint for the head, then, a safe passage had to be obtained for the medulla—that part of the great nerve stem which joins the brain to the spinal cord. The medulla is part of the brain stem.

This was only one of the difficulties which had to be overcome. The eyes are set on the pre-fulcral lever of the head. For our safety we must be able to look in all directions—over this shoulder or that. We must also be able to turn our heads so that our ears may discover in which direction a sound is reaching us. In fashioning a fulcral joint for the head, then, two different objects had to be secured : free mobility for the head, and a safe transit for the medullary part of the brain stem. How well these objects have been attained is known to all of us, for we can move our heads in the freest manner and suffer no damage whatsoever. Indeed, so strong and perfect is the joint, that damage to it is one of the most uncommon accidents of life.

Let us look, then, how this triumph in engineering has been secured. In her inventive moods Nature always hits on the simplest plan possible. In this case she adopted a ball-and-socket joint—the kind by which older astronomers mounted their telescopes. By such a joint the telescope becomes, just as the head is, a lever of the first order. The eyeglass is placed at one end of the lever, while the object-glass, which can be swept across the face of the heavens, is placed at the other or more distant end. In the human body the first vertebra of the backbone—the atlas—is trimmed to form a socket, while an adjacent part of the base of the skull is shaped to play the part of ball. Having thus hit upon the kind of joint to be used, the next point was to secure a safe passage for the brain stem. That, too, was worked

out in the simplest fashion. The central parts of both ball and socket were cut away, or, to state the matter more exactly, were never formed. Thus a passage was obtained right through the centre of the fulcral joint of the head. The centre of the joint was selected because when a lever is set in motion the part at the fulcrum moves least, and the medulla, being placed at that point, is least exposed to disturbance when we bend our heads backwards, forwards, or from side to side. When we examine the base of the skull all that we see of the ball of the joint are two knuckles of bone (fig. 11, A), covered by smooth slippery

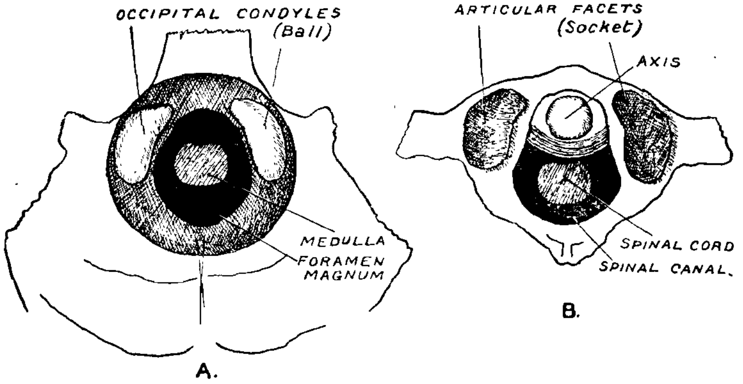


FIG. 11.—A, The opening in the base of the skull, by which the brain stem passes to the spinal canal. The two occipital condyles represent part of the ball which fits into the cup formed by the atlas. B, The upper surface of the atlas to show the parts of the socket on which the occipital condyles move.

cartilage or gristle, to which anatomists give the name of occipital condyles. If we were to try to complete the ball, of which they form a part, we should close up the great opening—the *foramen magnum*—which provides a passageway for the brain stem on its way to the spinal canal. All that is to be seen of the socket or cup are two hollows on the upper surface of the atlas into which the occipital condyles fit (fig. 11, B). Merely two parts of the brim of the cup have been preserved to provide a socket for the condyles or ball.

As we bend our heads the occipital condyles revolve or glide on the sockets of the atlas. But what will happen

if we roll our heads backwards to such an extent that the bony edge of the opening in the base of the skull is made to press hard against the brain stem and crush it? That, of course, would mean instant death. Such an accident has been made impossible (1) by making the opening in the base of the skull so much larger than the brain stem that in extreme movements there can be no scissors-like action; (2) the muscles which move the head on the atlas arrest all movements long before the danger-point is reached; (3) even if the muscles are caught off their guard, as they sometimes are, certain strong ligaments—fastenings of tough fibres—are so set as to automatically jam the joint before the edge of the foramen can come in contact with the brain stem.

These are only some of the devices which Nature had to contrive in order to secure a safe passageway for the brain stem. But in obtaining safety for the brain stem the movements of the head on the atlas had to be limited to mere nodding or side-to-side bending. The movements which are so necessary to us, that of turning our heads so that we can sweep our eyes along the whole stretch of the skyline from right to left, and from left to right, were rendered impossible. This defect was also overcome in a simple manner. The joints between the first and second vertebræ—the atlas and axis—were so modified that a turning movement could take place between them instead of between the atlas and skull. When we turn or rotate our heads the atlas, carrying the skull upon it, swings or turns on the axis. When we search for the manner in which this has been accomplished, we see again that Nature has made use of the simplest means at her disposal. When we examine a vertebra in the course of construction within an unborn animal, we see that it is really made up by the union of four parts (see fig. 12): a central block which becomes the "body" or supporting part; a right and a left arch which enclose a passage for the spinal cord; and, lastly, a fourth part in front of the central block which only becomes big and strong in the first vertebra—the atlas.

When we look at the atlas (fig. 12) we see that it is merely a ring made up of three of the parts—the right and left arches and the fourth element,—but the body is missing. A glance at fig. 12, B, will show what has become of the body of the atlas. It has been joined to the central block of the second vertebra—the axis—and projects upwards within the front part of the ring of the atlas, and thus forms a pivot round which rotatory movements of the head can take place. Here we have in the atlas an approach to the formation of a wheel—a wheel which has its axle or pivot placed at some distance from its centre, and therefore a complete revolution of the

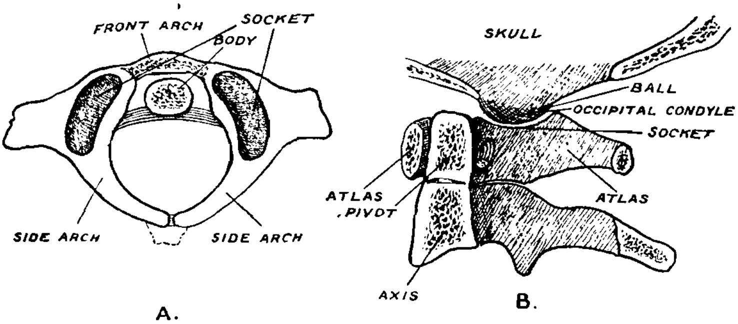


FIG. 12.—A, The original parts of the first or atlas vertebra. B, Showing the "body" of the first vertebra fixed to the second, thus forming the pivot on which the head turns.

atlas is impossible. A battery of small muscles is attached to the lateral levers of the atlas and can swing it freely, and the head which it carries, a certain number of degrees to both right and left. The extent of the movements is limited by stout check ligaments. Thus, by the simple expedient of allowing the body of the atlas to be stolen by the axis, a pivot was obtained round which the head could be turned on a horizontal plane.

Nature thus set up a double joint for the movements of the head, one between the atlas and axis for rotatory movements, another between the atlas and skull for nodding and side-to-side movements. And all these she increased by giving flexibility to the whole length

of the neck. Makers of modern telescopes have imitated the method Nature invented when fixing the human head to the spine. Their instruments are mounted with a double joint—one for movements in a horizontal plane, the other for movements in a vertical plane. We thus see that the young engineer as well as the student of medicine can learn something from the construction of the human body.

In low forms of vertebrate animals like the fish and frog, the head is joined directly to the body, there being no neck.

CHAPTER VII

THE FOOT AND THE FOREARM AS LEVERS

No matter what part of the human body we examine, we shall find that its mechanical work is performed by means of bony levers. Having seen how the head is moved as a lever of the first order, we are now to choose a part which will show us the plan on which levers of the second order work, and there are many reasons why we should select the foot. It is a part which we are all familiar with ; every day we can see it at rest and in action. The foot, as we have already noted, serves as a lever in walking. It is a bent or arched lever (fig. 14) ; when we stand on one foot, the whole weight of our body rests on the summit of the arch. We are thus going to deal with a lever of a complex kind.

In using a chisel to prise open the lid of a box, we may use it either as a lever of the first or of the second order. We have already seen (fig. 9) that in using it as a lever of the first order we pushed the handle downwards while the bevelled end was raised forcing open the lid. The edge of the box served as a rest or fulcrum for the chisel. If, however, after inserting the bevelled edge under the lid, we raise the handle instead of depressing it, we change the chisel into a lever of the second order. The lid is not now forced up on the bevelled edge, but is raised on the side of the chisel, some distance from the bevelled edge, which thus comes to represent the fulcrum. By using a chisel in this way we reverse the positions of the weight and fulcrum and turn it into a lever of the second order. Suppose we push the side of the chisel

—which is 10 inches long—under the lid to the extent of 1 inch, then the advantage we gain in power is as 1 to 10; we thereby increase our strength tenfold. If we push the chisel under the lid for half its length, then our advantage stands as 10 to 5; our strength is only doubled. If we push it still further for two-thirds of its length, then our gain in strength is only as 10 to 6·6; our power is increased by only one-third. Now this has an important bearing on the problem we are going to investigate, for the weight of our body falls on the foot, so that only about one-third of the lever—that part of it which is

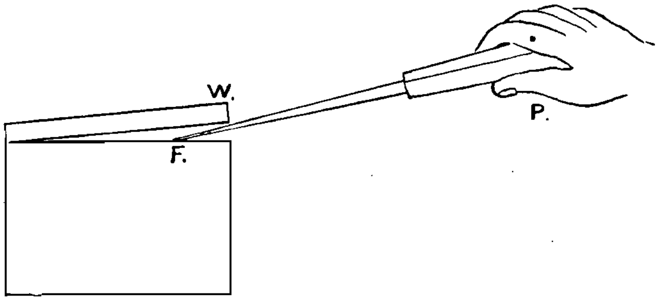


FIG. 13.—Showing a chisel used as a lever of the second order.

formed by the heel—projects behind the point on which the weight of the body rests. The strength of the muscles which act on the heel will only be increased by about one-third.

We have already seen that a double engine, made up of the *gastrocnemius* and *soleus*, is the power which is applied to the heel when we walk, and that the pad of the foot, lying across the sole in line with the ball of the great toe, serves as a fulcrum or rest. The weight of the body falls on the foot between the fulcrum in front and the power behind, as in a lever of the second order. We have explained why the power of the muscles of the calf is increased the more the weight of the body is shifted towards the toes, but it is also evident that the speed and the extent to which the body is lifted are diminished. If, however, the weight be shifted more towards the heel, the

muscles of the calf, although losing in power, can lift their load more quickly and to a greater extent.

We must look closely at the foot lever if we are to understand it. It is arched or bent; the front pillar of the arch stretches from the summit or keystone, where the weight of the body is poised, to the pad of the foot or fulcrum (fig. 14); the posterior pillar, projecting as the heel, extends from the summit to the point at which the muscular power is applied. A foot with a short anterior pillar and a long posterior pillar or heel is one

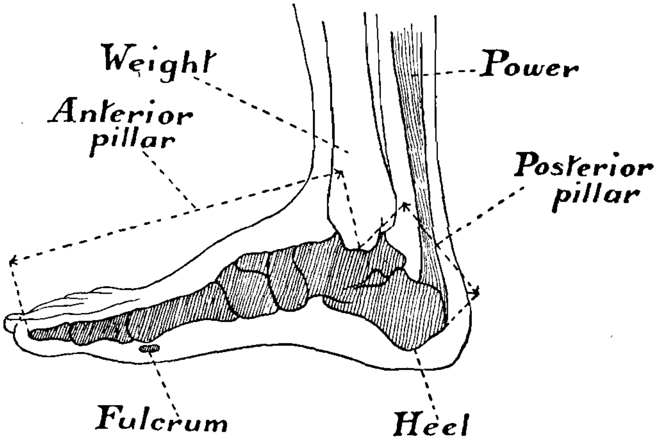


FIG. 14.—The bones forming the arch of the foot, seen from the inner side.

designed for power, not speed. It is one which will serve a hill-climber well or a heavy, corpulent man. The opposite kind, one with a short heel and a long pillar in front, is well adapted for running and sprinting—for speed. Now, we do find among the various races of mankind that some have been given long heels, such as the dark-skinned natives of Africa and of Australia, while other races have been given relatively short, stumpy heels, of which sort the natives of Europe and of China may be cited as examples. With long heels less powerful muscular engines are required, and hence in dark races the calf of the leg is but ill developed, because the muscles which move the heel are small. We must admit,

however, that the gait of dark-skinned races is usually easy and graceful. We Europeans, on the other hand, having short heels, need more powerful muscles to move them, and hence our calves are usually well developed, but our gait is apt to be jerky.

If we had the power to make our heels longer or shorter at will, we should be able, as is the case in a motor cycle, to alter our "speed-gear" according to the needs of the road. With a steep hill in front of us we should adopt a long, slow, powerful heel, while going down an incline a short one would best suit our needs. With its four-change speed-gear a motor cycle seems better adapted for easy and economical travelling than the human machine. If, however, the human machine has no change of gear, it has one very marvellous mechanism—which we may call a *compensatory* mechanism, for want of a short, easy name. The more we walk, the more we go hill-climbing, the more powerful do the muscular engines of the heel become. It is quite different with the engine of a motor cycle; the more it is used the more does it become worn out. It is because a muscular engine is living that it can respond to work by growing stronger and quicker.

I have no wish to extol the human machine unduly, nor to run down the motor cycle because of certain defects. There is one defect, however, which is inherent in all motor machines which man has invented, but from which the human machine is almost completely free. We can illustrate the defect best by comparing the movements of the heel with those of the crank-pin of an engine. One serves as the lever by which the gastrocnemius helps to propel the body; the other serves the same purpose in the propulsion of a motor cycle. On referring to fig. 15, A, the reader will see that the piston-rod and the crank-pin are in a straight line; in such a position the engine is powerless to move the crank-pin until the fly-wheel is started, thus setting the crank-pin in motion. Once started, the leverage increases, until the crank-pin stands at right angles to the piston-rod—a point of maximum

power which is reached when the piston is in the position shown in fig. 15, B. Then the leverage decreases until the second dead centre is reached (fig. 15, C) ; from that point the leverage is increased until the second maximum is reached (fig. 15, D), whereafter it decreases until the arrival at the first position completes the cycle. Thus in each revolution there are two points where all leverage or power is lost, points which are surmounted because

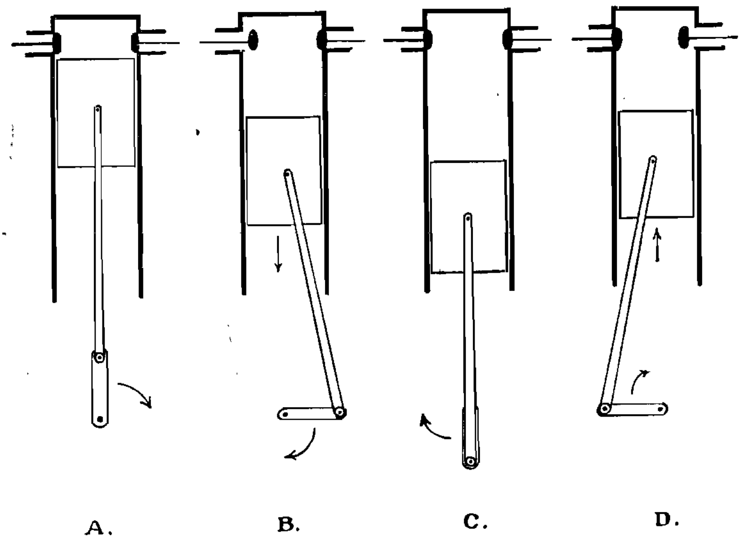


FIG. 15 —Showing the crank-pin of an engine at:

A, First dead centre.
B, First maximum leverage.
C, Second dead-centre.
D, Second maximum leverage.

of the momentum given by the fly-wheel. Clearly we should get most out of an engine if it could be kept working near the points of maximum leverage—with the lever as nearly as possible at right angles to the crank-pin.

Now, we have seen that the tendon of Achilles is the piston cord, and the heel the crank-pin, of the muscular engine represented by the gastrocnemius and soleus. In the standing posture the heel slopes downwards and backwards, and is thus in a position, as regards its piston

cord, considerably beyond the point of maximum leverage. As the heel is lifted by the muscles it gradually becomes horizontal and at right angles to its tendon or piston cord. As the heel rises, then, it becomes a more effective lever; the muscles gain in power. The more the foot is arched, the more obliquely is the heel set and the greater is the strength needed to start it moving. Hence, races like the European and Mongolian, which have short as well as steeply set heels, need large calf muscles. It is at the end of the upward stroke that the heel becomes most effective as a lever, and it is just then that we most need power to propel our bodies in a forward direction. It will be noted that the heel, unlike the crank-pin of an engine, never reaches, never even approaches, that point of powerlessness known to engineers as a dead centre. Work is always performed within the limits of the most effective working radius of the lever. It is a law for all the levers of the body; they are set and moved in such a way as to avoid the occurrence of dead centres. Think what our condition would have been were this not so; why, we should require revolving fly-wheels set in all our joints!

Another property is essential in a lever: it must be rigid, otherwise it will bend and power will be lost. Now, if the foot were a rigid lever there would be missing two of its most useful qualities. It could no longer act as a spring or buffer to the body, nor could it adapt its sole to the various kinds of surfaces on which we have to tread or stand. Nature, with her usual ingenuity, has succeeded in combining those opposing qualities—rigidity, suppleness, and elasticity or springiness—by resorting to her favourite device, the use of muscular engines. The arch is necessarily constructed of a number of bones which can move on each other to a certain extent, so that the foot may adapt itself to all kinds of roads and paths. It is true that the bones of the arch are loosely bound together by passive ties or ligaments, but as these cannot be lengthened or shortened at will, Nature had to fall back on the use of muscular engines

for the maintenance of the foot as an arched lever. Some of these are shown in fig. 16. The foot, then, is a lever of a very remarkable kind ; all the time we stand or walk, its rigidity, its power to serve as a lever, has to be maintained by an elaborate battery of muscular engines all kept constantly at work. No wonder our feet and legs become tired when we have to stand a great deal. Some of these engines, the larger ones, are kept in the leg, but their tendons or piston cords descend below the

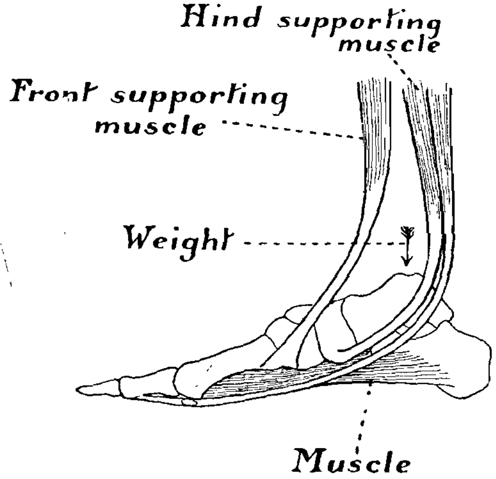


FIG. 16.—The arch of the foot from the inner side, showing some of the muscles which maintain it.

ankle-joint to be fixed to various parts of the arch, and thus help to keep it up (fig. 16). Within the sole of the foot has been placed an installation of seventeen small engines, all of them springing into action when we stand up, thus helping to maintain the foot as a rigid yet flexible lever.

We have already seen why our muscles are so easily exhausted when we stand stock-still ; they then get no rest at all. Now, it sometimes happens in people who have to stand for long periods at a stretch that these muscular engines which maintain the arch are overtaxed ; the arch of the foot gives way. The foot becomes flat

and flexible, and can no longer serve as a lever. Many men and women thus become permanently crippled; they cannot step off their toes, but must shuffle along on the inner sides of their feet. But if the case of the overworked muscles which maintain the arch is hard in grown-up people, it is even harder in boys and girls who have to stand quite still for a long time, or who have to carry such burdens as are beyond their strength. When we are young the bony levers and muscular engines of our feet have not only their daily work to do, but they have continually to effect those wonderful alterations

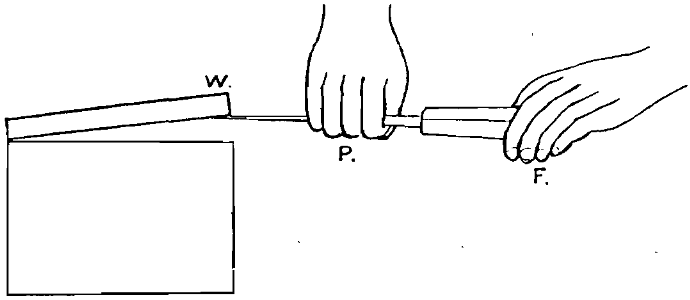


FIG. 17A.—A chisel used as a lever of the third order. W, weight; P, power; F, fulcrum.

which we call growth. Hence the muscular engines of young people need special care; they must be given plenty of work to do, but of that kind of exercise which gives them alternate strokes of work and rest. Even the engine of a motor cycle has three strokes of play for one of work. Our engines, too, must have a liberal supply of the right kind of fuel. But even with all those precautions, we have to confess that the muscular engines of the foot do sometimes break down, and the leverage of the foot becomes threatened. Nor have we succeeded in finding out why they are so liable to break down in some boys and girls and not in others. Some day we shall discover this too.

We are now to look at another part of the human machine so that we may study a lever of the third order

(fig. 17A). The lever formed by the forearm and hand will suit our purpose very well. It is pivoted or jointed at the elbow: the elbow is its fulcrum (fig. 17B). At the opposite end of the lever, in the upturned palm of the hand, we shall place a weight of 1 lb. to represent the load to be moved. The power which we are to yoke to the lever is a strong muscular engine we have already spoken about called the *brachialis anticus* or front brachial muscle. It lies in the upper arm, where it is fixed to the bone of that part—the humerus. It is attached to one of the bones of the forearm—the ulna—just beyond the elbow.

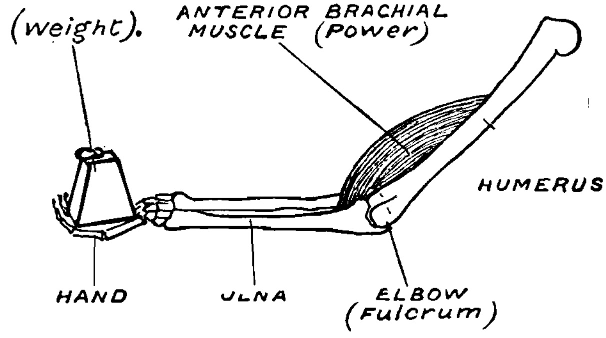


FIG. 17B.—The forearm and hand as a lever of the third order.

In the second order of lever we have seen that the muscle worked on one end, while the weight rested on the lever somewhere between the muscular attachment and the fulcrum. In levers of the third order the load is placed at the end of the lever, and the muscle is attached somewhere between the load and the fulcrum (fig. 17A). In the example we are considering the brachial muscle is attached about half an inch beyond the fulcrum at the elbow, while the total length of the lever, measured from the elbow to the palm, is 12 inches. Now, it is very evident that the muscle or power being attached so close to the elbow, works under a great disadvantage as regards strength. It could lift a 24-lb. weight placed on the forearm directly over its attachment as easily as a single pound weight placed on the palm. But, then, there is

this advantage: the 1-lb. weight placed in the hand moves with twenty-four times the speed of the 24-lb. weight situated near the elbow. What is lost in strength is gained in speed. Whenever Nature wishes to move a light load quickly she employs levers of the third order.

We have often to move our forearm very quickly, sometimes to save our lives. The difference of one-hundredth of a second may mean life or death to us on the face of a cliff when we clutch at a branch or jutting rock to save a fall. The quickness of a blow we give or fend depends on the length of our reach. A long forearm and hand are ill-adapted for lifting heavy burdens; strength is sacrificed if they are too long. Hence we find that the labouring peoples of the world—Europeans and Mongolians—have usually short forearms and hands, while the peoples who live on such bounties as Nature may provide for them have relatively long forearms and hands.

Now, man differs from anthropoid apes, which are distant cousins of his, in having a forearm which is considerably shorter than the upper arm; whereas in anthropoid apes the forearm is much the longer. That fact surprises us at first, especially when we remember that anthropoids spend most of their lives amongst trees and use their arms much more than their legs in swinging the weight of their heavy bodies from branch to branch and from tree to tree. A long forearm and hand give them a long and quick reach, so that they can seize distant branches and swing themselves along safely and at a good pace. Our first thought is to suppose that a long forearm, being a weak lever, will be ill adapted for climbing. But when you look at fig. 18, the explanation becomes plain. When a branch is seized by the hand, and the whole weight of the body is supported from it, the entire machinery of the arm changes its action. The forearm is no longer the lever which the brachial muscle moves (fig. 18), but now becomes the base from which it acts. The part which was its piston cord now serves as its base of fixation, and what was its base of fixation to the humerus becomes

its piston cord. The humerus has become a lever of the third order; its fulcrum is at the elbow; the weight of the body is attached to it at the shoulder and represents the load which has to be lifted. We also notice that the brachial muscle is attached a long way up the humerus, thus increasing its power very greatly, although

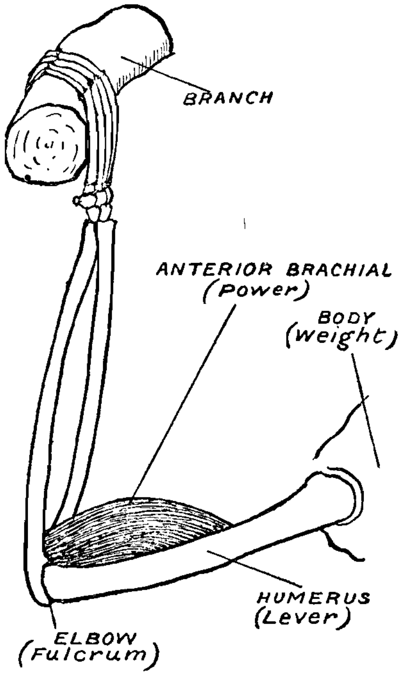


FIG. 18.—Showing the action of the brachialis anticus in the arm of an anthropoid ape.

the rate at which it helps in lifting the body is diminished. We can see, then, why the humerus is short and the forearm long in anthropoid apes; shortening the humerus makes it more powerful as a lever for lifting the body. That is why anthropoids are strong and agile tree-climbers. But then watch them use those long hands and forearms for the varied and precise movements we have to perform in our daily lives, and you will see how clumsy they are.

In the human machine the levers of the arm have been fashioned, not for climbing, but for work of another kind—the kind which brings us a livelihood. We must have perfect control over our hands; the longer the lever of the forearm is made, the more difficult does control of the hand become. Hence in the human machine the forearm is made relatively short and the upper arm long.

We have just seen that the brachial muscle could at one time move the forearm and hand, but that when they are fixed it could then use the humerus as a lever and thereby lift the weight of the body. What should we think of a metal engine which could reverse its action so that it could act through its piston-rod at one time and through its cylinder at another? Yet that is what a great number of the muscular engines of the human machine do every day.

There is another little point, but an important one, which I must mention before this chapter is finished. I have spoken of the forearm and hand as if they formed a single solid lever. Of course that is not so; there are joints at the wrist where the hand can be moved on the forearm. But when a weight is placed in the hand these joints become fixed by the action of muscles. The fixing muscles are placed in the forearm, both in front and behind, and are set in action the moment the hand is loaded. The wrist joint is fixed just in the same way as the joints of the foot are made rigid by muscles when it has to serve as a lever. Even when we take a pen in our hand and write, these engines which balance and fix the wrist have to be in action all the time. The steadiness of our writing depends on how delicately they are balanced. Like the muscles of the foot, the fixers of the wrist may become overworked and exhausted, as occasionally happens in men and women who do not hold their pens correctly and write for long spells day after day. The break-down which happens in them is called "writer's cramp," but it is a disaster of the same kind as that which overtakes the foot when its arch collapses, and its utility as a lever is lost.

CHAPTER VIII

BONE-BUILDERS AND THE MANNER IN WHICH THEY CONSTRUCT LIVING LEVERS

It has been your good fortune, I am sure, to peer through the window of an experimental hive and watch bees building the cells of their combs. They are noted as skilful masons, arranging their habitations according to the space at their disposal, and carrying out alterations in their arrangements should such be found to be necessary. Now, if we could peer into the substance of bone through the eye-piece of a microscope, we should see the interior of a hive of a different kind—a hive where minute cells are occupied by living microscopic units known to anatomists and physiologists as bone corpuscles or osteoblasts, but since they spend their lives in laying down and looking after bone we may name them "bone-builders." Although so minute these bone-builders are like bees in several respects. The building materials of the honeycomb are manufactured in the living tissues of the bee's body; the wax, when the bee is building, can be seen oozing from between the rings of the builder's abdomen. Bone-builders also employ materials which are formed in their own bodies in the formation of the cells or spaces in which they live. Perhaps it is when the honeycomb is filled with a brood of maggot bees that it most resembles bone, excepting that the cells or spaces of bone in which the osteoblasts live are so very small that they can be seen only by the aid of a microscope. The walls of these cells or spaces are enormously thick and strong, and are made up of lime salts in place of wax. Each cell or space is

occupied by a bone-builder or bone corpuscle, so small that one thousand of them may be set out in a row or rank within the space of an inch. An osteoblast not only builds up its cell, but can alter it or take it down again when that is found necessary. Thus every bone is built up by myriads of microscopic masons or engineers who are given permanent quarters in habitations of their own erection. We speak of a city as being alive with inhabitants and a honeycomb alive with bees, but when we speak of the bones of our bodies as being alive we mean more. For we find that when a bone-builder dies a curious change also comes over the wall of his habitation, which seems to indicate that it too dies, and therefore we may suppose that every particle of a bone is really alive.

There is one difficulty met with in the construction of bony levers which men who make levers of steel or of wood know nothing of. They make their levers and engines full size at once ; their creations are adults ; they are quite "grown-up" from the start. It is otherwise in the case of bony levers, which begin to be laid down when the human limbs are so small that they can scarcely be seen with the naked eye. On this microscopic basis the bone-builders begin their task of constructing the thigh-bone ; for twenty years or more they labour at it, enlarging it in definite directions, altering it, and all the time keeping pace with fellow-workmen who are employed in building up neighbouring muscles, arteries, veins, nerves, and skin. It is plain that all of these builders must work in harmony, otherwise chaos would result in the formation of the limb. Before birth the task of bone-builders is comparatively easy, for the unborn child is then more or less at rest, floating in and supported by the waters of the womb. Some time after birth, however, when the limbs come into almost constant use, all the bony levers of the limbs have still to be altered and extended. The bone-builders cannot put up a notice, "This lever is out of use owing to repairs" ; they have to carry on during the day when all the machinery of the human body is going full speed, as well as at night when it is slowed down. Under these

difficult conditions we shall find that bone-builders carry out remarkable feats of engineering.

Of the two hundred bones which make up the skeleton, we shall select the thigh-bone as an example for study; it is the longest and strongest lever in all the body. The stage in construction reached by it at birth is shown in fig. 19. From its upper to its lower end it measures

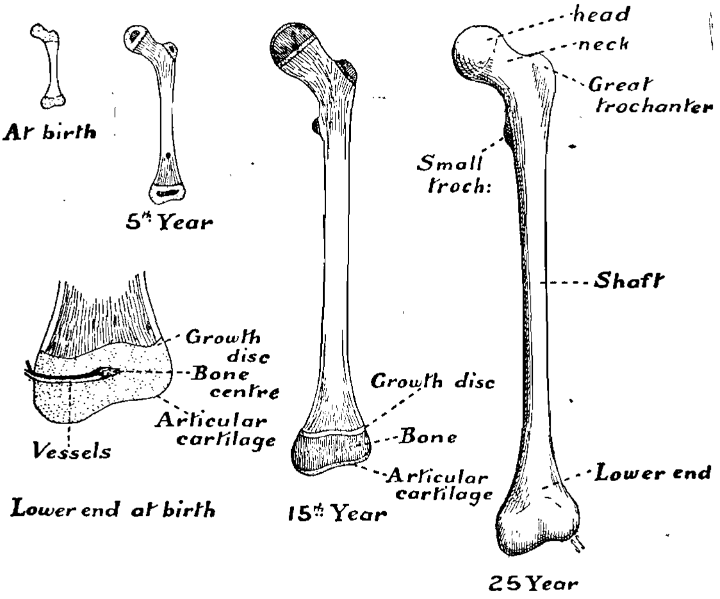


FIG. 19.—In this figure the following sections of the thigh-bone at various stages of growth are shown:—Section of the thigh-bone at birth to show its structure. Its lower end enlarged to show the centre of ossification and trail of blood-vessels. Section at the fifth year. Section at the fifteenth year. External form of the femur at the twenty-fifth year.

about 4 inches—less than a fourth of the length it will ultimately grow to. Only the shaft is made up of bone; it is formed not as a solid, but as a hollow pillar; its upper end, which fits into the socket of the hip-joint, is composed of pure gristle or cartilage; its lower end, meeting the tibia in the knee-joint, is also made up of cartilage. Within the lower cartilage, at the lower end, can be seen a spot of bone (fig. 19). Somehow a colony

of these microscopic bone-builders has pushed its way boldly into the very heart of the cartilage, its pathway being marked by a trail of blood-vessels which keep it supplied with the materials needed for future operations. When we examine the colony and its surroundings under great magnification we see that a kind of warfare is going forward. The bone-builders have not entered a virgin uninhabited territory. It is already occupied by builders of a more primitive kind, one which builds with cartilage, the original material used in the construction of levers in the animal body. The bone-building colonists in the lower end of the femur represent a more skilled kind of workman—a higher civilisation; before them the cartilage-builders fade away just as a primitive native race dies out before the advancing wave of European colonists. The bone-builders invade the homes of the cartilage corpuscles, rebuilding them in that curious and strong form of cement called bone. By the end of the first year another colony has established itself within the cartilaginous head at the upper end of the thigh-bone.[1]

When we turn to the stage of construction reached about the fifth year of life (fig. 19) we see that the bone-builders have been busy. They have added to the shaft, making it thicker as well as longer; the colony in the lower end has spread outwards; but the cartilage-builders have also been busy, so that the lower end of the bone is bigger in every way—both as regards its cartilage and its bone. So, too, in the upper end of the thigh-bone, the colony or "centre" in the head has increased its dominion; but the cartilage has grown as well. We notice that two other colonies have invaded the cartilage of the upper end—one in that outwork called the great trochanter, and another in a less projecting prominence named the lesser trochanter (fig. 19). By the fifteenth year a further stage is reached in the construction of the lever of the thigh. It is now three times the length it was at birth. The colonies of bone-builders have invaded almost the whole of the cartilaginous extremities, all save at certain places. At each end of the shaft a layer of cartilage still

[1] See Appendix D, p. 292.

persists, forming a partition between the lower end of the shaft and the lower colony or epiphysis ; and another between the upper end of the shaft and the colony of the head (fig. 19). In these discs or partitions of cartilage growth still goes on, and as the cartilage-builders lay down new material the adjoining bone-builders invade and occupy it. The cartilage partitions are constantly growing, and thus the length of the bone is being steadily increased. Growth in the length of the thigh-bone takes place in these discs, but increase in the thickness of the shaft and of the extremities is obtained by the deposition of new strata on the surface of the bone. Then, when we look at the thigh-bone as a finished lever (fig. 19) we notice that the growth discs of cartilage have disappeared, and that the end pieces of bone have become firmly annealed to the shaft. After a struggle lasting twenty years—sometimes more, sometimes less, depending on the individual—the cartilage-builders in the growth discs are vanquished by the armies of bone-builders, which fuse together across the cartilage chink, and thus the thigh-bone becomes a solid lever from end to end. When that has happened there can be no more growth in length ; our stature has then reached its zenith.

It is estimated that about two millions of bone-builders are already engaged in the construction of the thigh-bone of a newly born child ; by the time their task is completed an army of one hundred and fifty millions is employed on the task. Nor is this army demobilised when growth is over ; it is maintained as a standing army to look after the works and to effect repairs. If, for example, the thigh-bone should be broken, then the neighbouring regiments of bone-builders are instantly summoned to begin the laborious task of mending the breach.

The growth discs are clearly very important as well as very ingenious contrivances to allow bony levers to grow in length without interfering with their daily work. It is easy to see why they were not placed on the ends of bones ; the upper end of the thigh-bone is kept constantly moving in the socket of the hip-joint ; the lower

end rubs against the tibia in the knee-joint; had the growth discs been placed on the ends they would have been exposed to constant disturbance. And yet the growth discs are sometimes disturbed. When children are wrongly fed the regular and orderly warfare in the growth discs no longer goes on, and the child becomes "rickety" and its growth stunted. Then there is another disturbance which may take place; the cartilage-builders of the growth discs, for some reason we do not yet understand, go on strike; the bone-builders, while they keep on laying down surface layers and thus increasing the thickness of the bone, can make no headway at the growth discs, and hence the bones laid down are very short, thick, and stumpy. The boys and girls who suffer from this condition grow into strong, thickly set dwarfs, examples of which can be met with in the streets of all towns and cities. The disturbed growth from which they suffer is called *Achondroplasia*, which means a lessened growth of cartilage. It is this kind of dwarf which plays the part of gnome in fairy stories; in olden times kings kept them as jesters. In some children a blight falls on the bone-builders as well as the cartilage-builders of the entire body; the boy or girl who is afflicted with this condition remains childish in height and appearance as long as life lasts. Then there is another very marvellous transformation which may overtake growth discs. Usually it occurs just when manhood or womanhood is being reached; suddenly the cartilage- and bone-builders become excessively active, and in the course of three or four years the sufferers shoot up into giants. In recent years medical men have made discoveries which explain this growth madness. It is very clear that there must be some way of regulating the rate of growth in all the cartilage discs, otherwise the discs of one bone might grow too much while those of its neighbour did not grow enough. Now, all the bone-builders are given a very liberal supply of blood for their nourishment; bones are permeated with a fine meshwork of vessels, and in the blood are certain substances—we may even

call them drugs—which affect the working capacity of both cartilage-builders and bone-builders. They can incite them to work or send them to sleep. These substances or drugs are manufactured in small out-of-the-way workshops called *glands of internal secretion.* One of these lies within the skull, attached to the base of the brain, and is known as the pituitary gland. In giants this gland is always greatly and abnormally overgrown. We have reasons for supposing that it has thrown a drug or drugs into the blood which set all the bone-builders into a state of frenzied activity, producing the dire disease of growth called giantism.

We have been speaking of the bone-builders as if they were mere journeymen bricklayers. We have only to look at the manner in which they have built the upper end of the thigh-bone to see that they are highly accomplished engineers (fig. 20). The upper end of the thigh-bone is a bent lever ; for one instant in every step the weight of the whole body rests on the ball-like head of the lever ; the weight is transferred to the shaft of the bone through the neck which rises upwards obliquely from the shaft. The junction of the neck with the shaft is obscured by two bony projections which serve as cranks for muscles of the hip-joint, the greater and lesser trochanter (fig. 20).

The construction of bent levers is a matter to which engineers have had to give a great deal of attention, for it is clear that if the bent part—represented by the neck of the femur—is not rightly planned, it will be liable to snap under an undue weight. The construction of the neck of the upper end of the thigh-bone can be studied in the living bone as well as in the dead one. Fig. 20 represents a picture of it taken by X-rays. We see that the bone-builders or osteoblasts have laid down and fixed their struts and ties in a very elaborate and ingenious manner. From the inner wall of the hollow cylindrical shaft (fig. 20) issues a great spray of fine plates or beams of bone which ascend to end in the head, shaped like a half-ball ; they serve as struts, and receive the chief pressures or weights falling on the head of the thigh-bone. Then

from the outer wall of the cylindrical shaft rises another spray of fine plates or beams which, arching into the neck, end by interlacing with the struts rising from the inner side of the shaft. This second system serves as ties for the first series, and thus strengthens the neck and

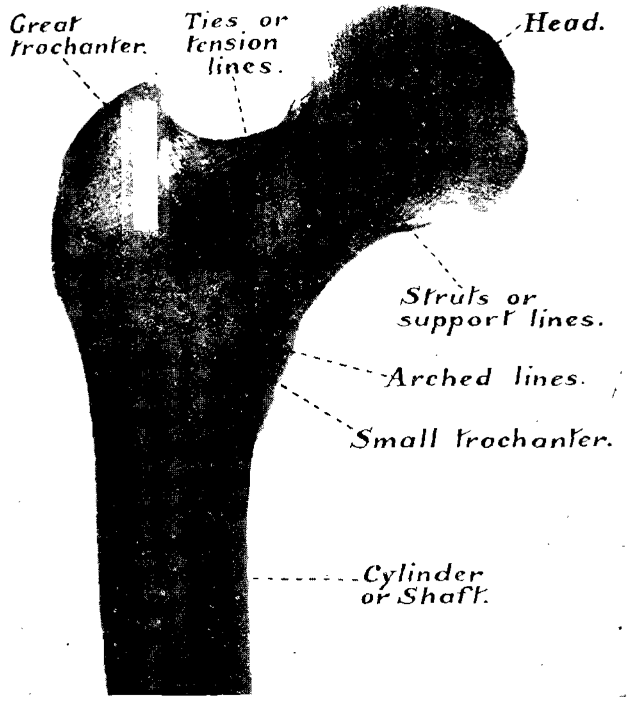


FIG. 20.—An X-ray picture to show the design or construction of the upper end of the thigh-bone.

helps to transmit the weight falling on the head of the bone to the outer wall of the shaft. In 1867 Professor Culmann, a famous Swiss engineer and mathematician, paid the bone-builders of the neck of the femur a great compliment. The design they employed, he found, was exactly similar to that applied in the Fairbairn crane—

the most perfect of all levers which man has invented for the lifting of heavy weights. Every beam of bone in the neck of the femur, he said, had been given the shape, thickness, and position which ensured the greatest strength with the greatest economy of material. Everywhere in the body we find the same perfect design in the work of bone-builders.

What is still more wonderful, is the fact that these

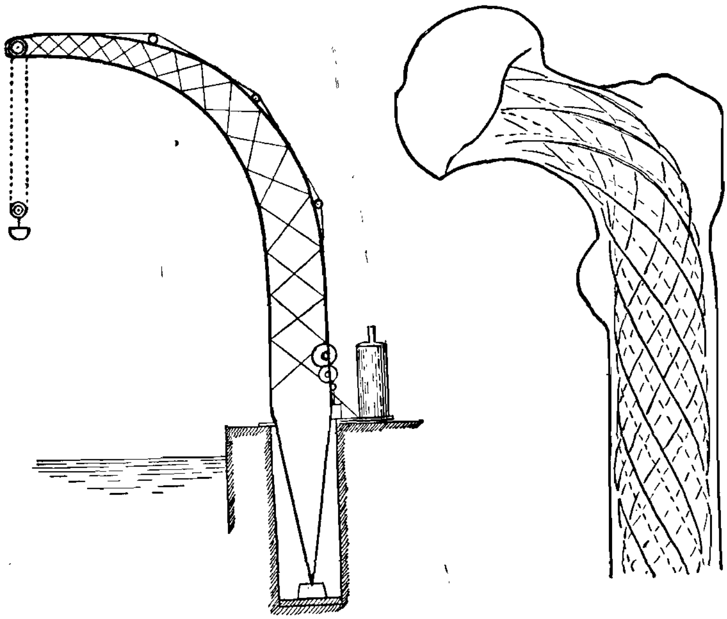


FIG. 21.—The construction of the upper end of the thigh-bone, as depicted by Professor F. Dixon, compared with a drawing of Fairbairn's crane (W. Finerty).

elaborate bony constructions are being constantly altered and rebuilt during the twenty years of growth. This can best be understood by looking at fig. 22. The upper part of a thigh-bone in the fifth year of growth is represented (A); when growth has proceeded to the fifteenth year the head and neck will have reached the position shown on the figure. Now, if growth were merely a stretching of the shaft, the architecture of the neck would merely be pushed up and enlarged to match the increase in the size

of the whole bone. There would be no need to rebuild it. But we have already seen that growth in length takes place at the disc under the head of the bone and along the upper surface of the neck. While bone is being laid down on the upper surface of the neck, it is necessary that material be cut away from its lower surface, otherwise the neck would become enormously thick and unwieldy (fig. 22, B). This the bone-builders do ; while

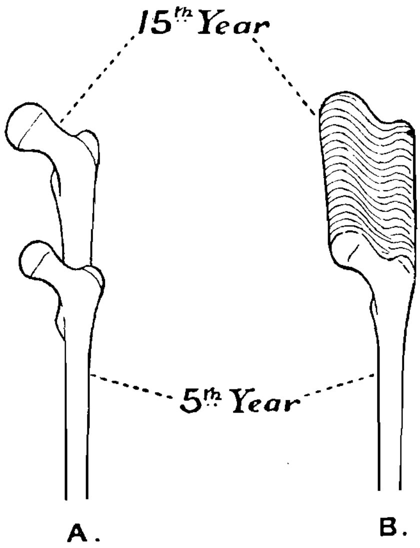


FIG. 22.—A, The upper end of a thigh-bone at the fifth year, above which is indicated the position which the head and neck will occupy when the fifteenth year is reached. B, The form which the upper end of the femur would assume if there was no remodelling.

they lay down new material on one side of the neck, they remove it at the other. The myriads of osteoblasts which have charge of the upper end of the cylindrical shaft have also a busy time, for the shaft is being expanded upwards at the expense of the struts and ties which ascend from it to strengthen the neck. Hence the whole architecture of the neck has to undergo daily alterations ; every strut and tie is ever being moved. Thus, as long as the thigh-bone grows, its upper extremity is always

being remodelled, but the bone-builders never lose their design for a single moment.

Bone-builders are the most economical of engineers. They fashion all their levers and props so that they obtain the greatest strength with the least possible outlay of material. It is so important for the human body, as indeed it is for every kind of machine, to be made as light as is compatible with strength. When the bicycle-maker uses iron tubes for the framework of his machine, he merely copies the design used in the animal machine. The bone-builders, too, know all about the "factor of safety law." Their levers are made strong enough to withstand a load which will carry ten times or more the one they are called upon to bear in their usual work. Yet occasionally a bone is broken, not by an accident or fall, but by the muscles which normally act on it. I have seen a humerus which was broken in the act of throwing a hand-bomb, but such mischances are very uncommon.

Mention has already been made of the manner in which osteoblasts mend the breach in a broken bone. But even if a bone only becomes bent, as bones are apt to do in rickets, the osteoblasts, lying in the hollow of the bend, immediately begin to throw out a buttress to strengthen the bone on its weak side. Nay, at times they have to take over the duties of an undertaker. Occasionally it happens, as the result of a blow or as an effect following disease, part of a bone dies. When this happens, the bone-builders immediately surrounding the dead area set to work and cut away all the bonds which unite the dead area to the living lever and cast the dead piece out. It is a slow process, and sometimes the surgeon, taking pity on their distress, relieves them of their toil and frees the dead part by the use of a chisel. Thus the lever-builders of the human machine are designers worthy of the closest study by young engineers as well as by students of medicine.

CHAPTER IX

A PERFECT LUBRICATING SYSTEM

We are now to see how a certain difficulty, one which taxes the ingenuity of designers of all kinds of moving machines, has been successfully surmounted in the construction of the human body. The difficulty is that of making one part rub or move on another—the piston within its cylinder, the axle within its bush—with the least amount of friction, and therefore with the least waste of power. No matter how truly a shaft is made and set within its bushes, or how perfectly the shaft may revolve within its bearings, friction of the grossest kind will still be produced, with the result that the engine wastes its power in making its joints red-hot, thus ruining the essential parts of its machinery. But if we separate the shaft from its bearings by a coating of oil and succeed in maintaining this coating in place, then friction will be reduced to a minimum; the bushes remain cool, and the power of the engine is expended in work. The ideal system which engineers seek to discover is one which will maintain a delicate and uniform film of oil between moving surfaces. The particles of the oil film act as microscopic ball-bearings, on which the revolving shaft turns. But the ideal system is difficult to come by for two reasons: (1) every shaft or axle tends to squeeze the film from that part of the bearings on which the pressure is greatest—just the situation where the film is most needed; (2) the film is constantly wasting from such friction as is unavoidable, hence this waste has steadily to be made good.

One has only to compare the older with the newer models of motor cycles to see how makers have struggled and are struggling to overcome the difficulties of lubrication. In the older models the driver was instructed to give his machine a "pumpful" of oil from time to time—every twenty minutes if he was making twenty miles an hour; more frequently in taking a steep hill, less frequently when his machine was running easily. The oil so injected found its way to the bottom of the crank-case, where the whirling flywheel picked it up and flung it into every corner of the engine—lubricating piston, cylinder, and all the bearings of its machinery. The system was laborious and wasteful; after every pumpful the engine passed from a surfeit to a dearth. If the driver was forgetful or if a feed-pipe became choked, the finest machine ran the risk of ruin. Then came the "drip-feed" system, by which the joints were given a steady supply of lubricant; contrivances were discovered by which the supply could be regulated according to the need of the machine—greater when the engine was running under stress, less when it was running easy. But even then the system was far from perfect; the films of oil which coated the revolving shafts were not uniform; at the side of the joint where the greatest pressure fell, the film was broken; there the metal surfaces were apt to touch and rub against each other. Engineers have discovered only one way of overcoming this difficulty, and that is by making the axle-boxes so perfectly enclosed that oil can be forced into them by a pump at such a pressure as will overcome that between the shaft and its bearings, and thus interpose between them a perfect coating or film of oil. No machine has yet been fitted with a system which maintains a uniform film of lubricant between the moving surfaces of its joints except one, and that is the animal machine. We can best study this perfect lubricating system in the human body.

We have already seen that hundreds of engines and levers are used in the construction of the human machine.

That implies a large number of surfaces which move or rub on each other—a great number of joints. Counting both great and small, there are altogether 25 joints connected with each lower limb ; 50 joint bearings therefore have to be kept lubricated during each step. In the backbone, which we have seen is also set in motion when we walk, there are 46 bony surfaces which rub and glide the one upon the other. They, too, have to be kept oiled. Then in connexion with the ribs and breast-bone, movements take place at 84 joints—all of them quite small—with every breath we take. There is no rest at these joints ; they are in motion night and day. There are only four joints connected with the head, two where it is poised on the backbone and two where the lower jaw is jointed to the base of the skull, just in front of the ear passages. Sometimes, especially if we have had to chew very tough substances or have been talking and laughing too much, we may hear the joints of the lower jaw actually creak, as if they were short of lubricant. Further, in each upper limb there are 23 joints. All told there are 230 joints in the human body, varying in degrees of magnitude and of importance. A swimmer sets all of these in motion—one after the other—as he plies his limbs and moves his body. We are in reality multi-articular machines. There is no need to emphasise the necessity of a perfect lubricating system for the human body, seeing how extensive the rubbing surfaces are.

We can best understand the lubricating system which Nature has invented and applied in our bodies by a single example—such as that offered to us in the ankle-joint. In fig. 23 this joint has been laid open by a vertical cut of the leg and foot, one which exposes the tibia—the chief lever of the leg—and the manner in which that lever is jointed to the ankle-bone or astragalus. We may look on the tibia as a spoke of a wheel and the astragalus as its axle. The tibia is a spoke which can rotate only within a limited part of a circle ; when the foot rests on the ground and the tibia turns forward a little way, the

margin of its lower jointed end becomes jammed against the ankle-bone ; the same thing happens when it is bent too far backwards. In life, however, the muscles and tendons passing from the leg to the foot arrest the movements before jamming is possible. We must notice, too, another feature of the ankle-joint : when the foot is firm on the ground it is the tibial spoke which rotates ; but if the foot is free and the spoke fixed, then it is the astragalus —the axle of the foot-lever—which rotates. In either

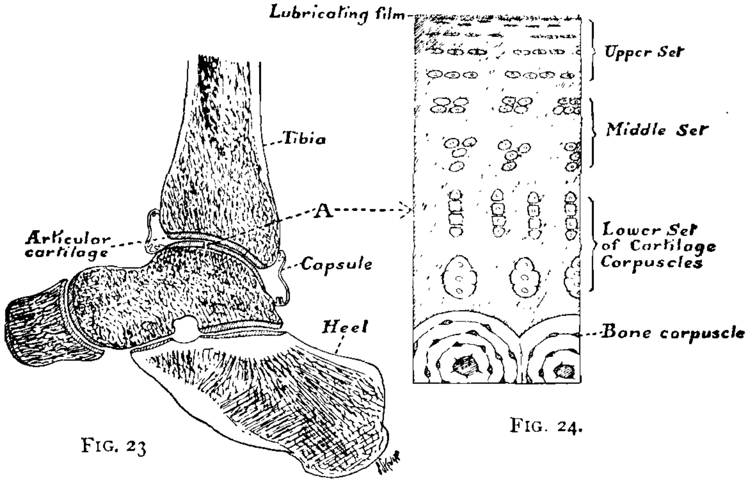


FIG. 23 FIG. 24.

FIG. 23.—A vertical section of the ankle-joint, exposing the lower end of the tibia and astragalus.

FIG. 24.—A magnification of the part of the ankle-joint cartilage indicated by the line A shown in fig. 23.

case the lower end of the tibia rubs or glides upon the upper surface of the astragalus. When the whole weight of the body is poised on one leg, as it is with every step we take, it is clear that the lower end of the tibia must press heavily on the upper surface of the astragalus, and unless the joint is provided with a perfect mechanism for preventing friction, it must happen that the opposed surfaces will rub each other away until both tibia and astragalus are entirely consumed.

The mechanism is a simple one. The rubbing surfaces

of the two opposed bones are coated with a thin layer of cartilage, less than an eighth of an inch in thickness. We notice, too, that this covering of cartilage is most firmly fixed to the terminal surfaces of bones; indeed, as we have already seen, it is part of the end cartilage which has survived the onslaught of the invading osteoblasts. One observes, also, when one presses on the cartilage that it yields or flattens, but when the pressure is withdrawn it springs out again, showing that the cartilage which lines joints is elastic and can serve as a buffer. Its surface, too, is always covered by a film of substance named synovia, which is not unlike white of egg in appearance, but so slippery that cartilage escapes from our fingers should we try to grasp a bone by its articular end. As for colour, joint cartilage is pearly-white, there being no tinge of red in it, for it is perfectly bloodless. Not a vessel, not even a red blood corpuscle, crosses its threshold. And yet the cartilage which lines every joint of the body, as well as the ankle-joint, is alive. We have seen that cartilage is studded with living microscopic units which surround themselves with thick, soft walls of that rubber-like substance which anatomists have named chondrin. For that reason cartilage corpuscles must be provided with sustenance, for all things which are actively alive must be constantly nourished.[1]

In order to see how cartilage and "cartilage-builders" live and work as engineers and lubricators, a small part of the articular cartilage of the ankle-joint indicated in fig. 23 has been magnified fifty times and drawn in fig. 24. The spaces in the bone, immediately under the attached surface of the thin cartilage plate, are richly supplied with blood, yielding more than can be needed by the neighbouring bone-builders. Hence we suppose that the cartilage-builders draw their nourishment from the vessels of the underlying bone, imbibing merely the fluid part of the blood—its plasma. We notice, too, that the cartilage-builders have arranged themselves in three tiers or sets within the articular plate (fig. 24). In the middle stratum of the cartilage plate they are loosely grouped in irregular

[1] See Appendix E, p. 294.

troops; in the deeper stratum they form single files, as if they were advancing towards the underlying bone spaces; in the more superficial stratum they are compressed into ranks or rows, parallel to and advancing towards the rubbing surface. As they approach towards the surface, the cartilage-builders become flattened and the outlines of their bodies blurred. To the naked eye the rubbing surface seems perfectly smooth, but under the microscope we can see minute pits on it. When we examine such a pit with care we can usually find in it some trace of a ground-down cartilage-builder. Those surface rows of builders are advancing to make good the waste entailed by the rubbing of one articular plate on the other. We can see any day the same kind of thing happening in our skin; in every movement of our bodies our under-garments rub off the dried mummified remains of epidermis which is being shed by the skin. But there is this difference: when a cartilage-builder is sacrificed on the altar of duty, it does not become withered and dry like the scales of the cast-off scarf skin, but becomes soft and slippery; its body is turned to synovia—the oil or lubricant of joints. Here, then, is an easy way not only of making good the wear of a joint, of both shaft and bearings, but of keeping constantly between them a thin uniform film of lubricant—the ideal which engineers dream of but cannot attain. Yet Nature has worked the ideal out in the joints of our bodies by the simple method of using cartilage-builders to make good the wear of the joint surface, and then when their working days are over dissolving their bodies to form a lubricant!

We must not overlook certain other difficulties connected with joint construction which Nature cleverly surmounted at the same time. In a perfect system the supply of lubricant must be in proportion to the amount of work done. If there is more work done a greater supply of oil will be necessary. In Nature's system the supply of oil is automatic; the more the joint surfaces move on each other, and the greater the pressures brought

to bear on these surfaces, the greater is the response of the cartilage-builders, the more rapid is their destruction, and therefore the more plentiful the supply of synovia. But what becomes of the waste lubricant—for even a film of oil is not permanent? Every lubricant undergoes changes which, in course of time, unfit it for further service, hence it must be drained off and replaced. All of Nature's joints are completely enclosed spaces—enclosed by flaccid membranes which are loose enough to allow the adjacent levers to carry out all their normal movements (fig. 23). There is no empty space in Nature's joint boxes; synovial covered surface rubs on the surface set against it; only a lubricant film of synovia lies between them. There is no drain-pipe for the escape of lubricant. Nature is too economical for that. Into the crevices of the joints there project certain soft, warty fringes which have the power of absorbing and returning to the general system by way of the blood stream all the waste lubricant produced at articular surfaces.[1]

Many men and women pass through life and never have cause to know that the easy movement of the human machine is dependent on a lubricant system—so perfectly does it serve their needs. Even at the age of seventy human axles and bearings may be as fresh and unworn as in the hey-day of youth. That bugbear of the motor-driver—the sudden "seizing" of joints—never troubles the drivers of the human machine. And yet to many people—especially as years crowd over them—a peculiar kind of "seizing" does happen. From some cause we have not yet discovered, the lubricant system fails—in one joint or in several. Then the one cartilage plate begins to rub stiffly on its opponent; there is friction; and the articular plate wears in patches. The cartilage-builders, in place of melting down and becoming a slippery lubricant, remain obdurate and fibrous. The cartilage plates become leathery in consistence and ultimately worn through in places. The neighbouring bone-builders, which are saved from all forms of friction in healthy joints, become disturbed by

[1] See Appendix E, p. 294.

the grating in the articular plates and build wildly, throwing out knarled outgrowths of bone round the affected joint. With each movement a distinct creaking sound can be heard. This is the condition which we call chronic rheumatism; it is a veritable "seizing" of the joints, because the lubricant system has broken down and we have not yet learned how to set it right again. The fault lies with the cartilage-builders. They grow as before and seek to make good the waste that arises from wear, but fail us in their final sacrifice. Instead of disappearing into oil, they turn to a stiff leathery residue which clogs and wears the surfaces of joints.

In a motor cycle the movements of the piston-rod are quite free; it moves in air. But the piston cords of muscular engines have to work amidst the pressure and obstruction of surrounding tissues, and are thus exposed to friction. Here again Nature shows her ingenuity. Her handiwork is best studied at the wrist or ankle. Around the wrist- and ankle-joints we can feel the moving sinews or tendons of the muscles—often working round sharp curves. In such positions piston cords are made to work in lubricated tunnels. Not only is the tunnel lined with a self-lubricating cover, but the surface of the piston cord itself has a similar coating. Here again we have moving surfaces separated by a fine film of lubricant. The fingers and toes are tunnelled for the passage of the tendons which work their triple joints.

The perfection of this lubricating mechanism lays the human body open to certain dangers. Joint surfaces or tendon sheaths, should they be injured or sprained or should they be accidentally cut into, give disease-producing germs gateways through which they may flood the body. In such cases Nature usually responds by closing up the avenues of access—obliterates the lubricant spaces by sealing their opposed surfaces together. Thus it comes about—as a sequel to infected wounds of the hand or of the foot, or after severe sprains—that the

wrist- or ankle-joints remain stiff and of little use, because the piston cords of these muscular engines are tied to their tunnels by adhesions. Even here Nature steps in and offers a remedy. Exercises and movements of the fingers and hand, of the toes and foot, will gradually stretch the adhesions until they are long enough to permit the return of a normal range of motion.

CHAPTER X

WHAT HARVEY WAS TAUGHT CONCERNING THE HEART

Until now we have been examining the locomotive machinery of the human body—its muscles or engines, its levers or bones, and its joints or bearings. These structures make up a large part of the human machine. My learned friend, the late Prof. Alex. Macalister[1] of Cambridge University, has estimated that in a man of middle size the locomotive system should weigh about 80 lb. The bones, 200 in number, make up 20 lb. of that amount, while the muscles, of which Prof. Macalister counts 260 pairs, make up the remaining amount—60 lb. Thus the locomotive system represents about three-fifths of the total weight of the human machine. Now, we have seen that this mass of machinery can be kept going only if it is supplied with certain materials; the muscular engines need to be continually stoked, while the masons in the bones and the lubricators at the joints must have their stores constantly replenished. Nature has met these needs by adopting another contrivance—one which man discovered for himself long ago and with which we are all familiar—the pump. The heart of the human body is a pump—one which in the ingenuity of its construction, the delicacy of its regulation, and the effectiveness of its work far surpasses any model of man's invention.

It seems difficult for us to believe that there ever was a time when men did not know that the heart was a pump. Yet such was the case. The story of that discovery is a romance of real life—the story of adventure

[1] *Man Physiologically Considered.* Present Day Tracts, 1891.

made three centuries ago by William Harvey. We are to follow him from a May morning in 1593 when, as a lad of 15, he set out from the King's School, Canterbury —a school which still nestles in the shadow of the great cathedral,—to become a student of Caius College, in the University of Cambridge, until 1616 when, at the age of 38, he gave his first anatomy lecture in the College of Physicians—again under the shadow of a cathedral—old St Paul's in London. The journey began when Elizabeth was Queen and ended as King James became seated on her throne. It was a proud time for England. Shakespeare was pouring the boundless riches of his mind in her lap, and her sons, while laying the foundations of an Empire in the East and a Republic in the West, were flooding her shores with a rising tide of commerce. Indeed it was in this tide that Harvey was born ; his father lived at Folkestone, and shared in the prosperity of the port ; there Harvey was born on a highway to the uncharted seas, with the career of a buccaneer open to him. Fate turned his face in another direction and made this quiet, modest Elizabethan gentleman a pioneer in a realm towards which Englishmen of that time were not drawn—the realm of Natural Knowledge. This new kind of buccaneer was a lad of slight build and small stature, with dark intelligent eyes, black hair, delicate features, loving his pen rather than his sword ; and yet when pushed to it could wield a mental rapier with deadly effect.

We thus make the acquaintance of William Harvey as a lad of 15, on his way to become a student of Caius College, Cambridge—one which attracted then, as it still does, young Englishmen who wish to become physicians. We need not spend time on his student career at Cambridge, because the medical knowledge then taught in England had to be imported—imported from the busy flourishing universities in the north of Italy. It was then, as it is now : young Englishmen in search of knowledge wish to drink at the fountainhead, no matter what the trouble or the expense may be. Hence at the close of the

sixteenth century, after he had spent six years at Cambridge, we have to follow young Harvey to the most famous school of anatomy then in Europe, the University of Padua, which drew its students from Venice much in the same way as Oxford and Cambridge now attract the youth of London. Reaching that ancient university, he sought out Fabricius, the Professor of Anatomy, a man already past his sixtieth year and renowned far and wide for his learning and discoveries. The lecture theatre in which Harvey listened to him and watched him demonstrating the various structures of the human body is still standing, its narrow, time-worn seats rising tier upon tier. We are to join Harvey in that theatre as he takes his place in a jostling strange-costumed crowd of men, both young and old, rich and poor, to listen to Fabricius while he explains the course of the blood and the use of the heart. The uses of the various parts of the human machine, we find, are explained in a way which leaves no doubt or obscurity in the minds of the audience. There was, in the first place, the manufacture or concoction of blood ; that was the duty of the stomach ; it concocted food and turned it into blood, which was then passed on to the liver by means of the portal vein (fig. 25). The use of the liver was to transform the nutritive blood received from the stomach into real blood, blood which was endowed with "natural spirits" and therefore, being living, was fit to nourish the tissues of the body. Fabricius showed to his audience the two great veins which issued from the liver and then traced them towards all parts of the body. A great channel (the lower caval vein) conveyed the blood downwards to nourish the lower limbs ; another (the upper caval vein) issuing from above the liver carried the blood into the upper half of the body to nourish the arms and the head, neck, and brain. As it passed through the thorax, the upper caval vein ran directly through the right auricle of the heart (fig. 25). Thus the use of the liver and the meaning of the distribution of veins to the utmost parts of the body were fully explained ; they formed a blood system by which

nourishment was conveyed from the stomach and bowel

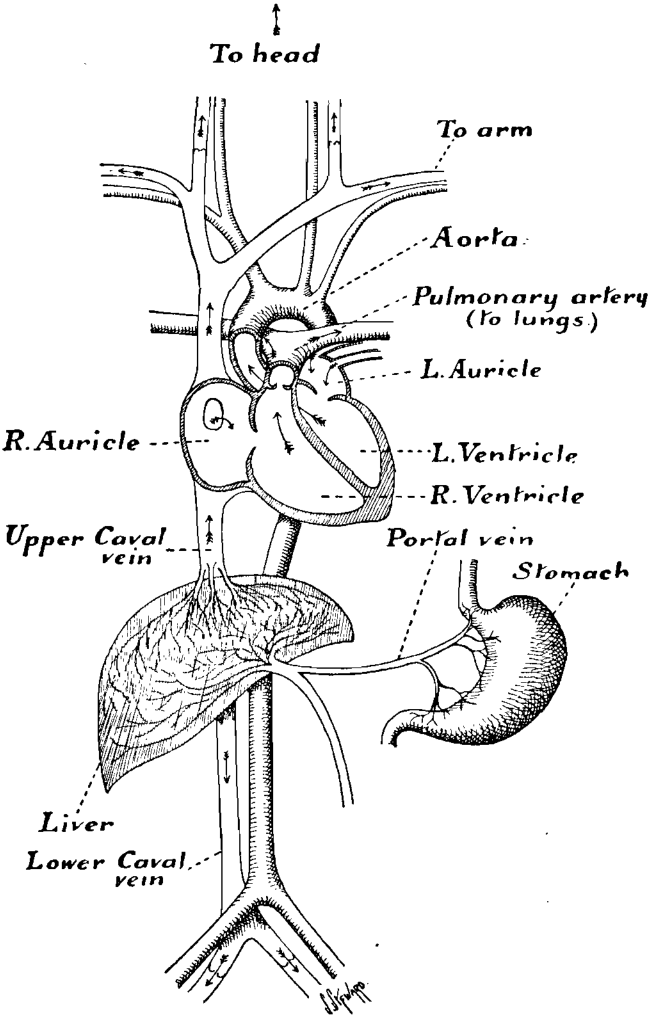


FIG. 25.—A diagram to illustrate what Harvey was taught concerning the veins and arteries.

to feed the living tissues of the body. As far as the veins were concerned there was apparently nothing left for William Harvey to discover.

Our interest in the lecture quickens as the learned Fabricius goes on to explain the use of the heart. "Cut it out of a living body and what happens?" he asks. That body dies and grows cold, a convincing proof for him that the heart is the source of both life and heat. He saw it as a vat or retort in which the "vital spirits" of life are brewed and mixed with blood. The "vital spirits" endowed the tissue of the body with life, and hence a great channel, the aorta, led out from the main chamber of the heart—the left ventricle. From the aorta there opened out other channels or arteries, passing to the arms, to the head, neck, and brain, while the aorta itself, after descending within the thorax and abdomen, ended by dividing into the two great arteries of the lower extremities (fig. 25). By means of these arteries the heart distributed life and heat to all parts of the body. Anyone could prove that what he taught was true by simply tying the main artery going to a limb. Thereby the limb was cut off from its source of heat and life; it became cold and mortified. Every part of the body was therefore supplied with a double set of vessels: (1) veins which conveyed nourishing blood, (2) arteries carrying blood which was endowed with life and heat. So Fabricius thought.

The heart, he believed, could give out life and heat to the tissues of the body only if it were supplied with two things—air and blood. That both of these were richly supplied to the heart all the world knew. Every breath drawn was designed to furnish the heart with air. The air was drawn down the wind-pipe or rough artery (trachea) to reach the lungs; there it was taken up by certain vessels in the lungs—the pulmonary veins—and conveyed by them to the left chambers of the heart, first to the left auricle and then to the left ventricle, the chief brewing chamber. It was therefore easy to understand why we breathed and why there was a trachea and lungs. It was clear why a man died when he choked; the air could no more reach the heart; vital spirits could no longer be concocted, and hence immediate death ensued. Here again knowledge seemed perfect; no discovery remained to be made.

But how did the blood reach the left chamber of the heart? When it reached that chamber there was no doubt concerning what happened to it; it became mixed with air and, in the mixing, vital spirits and heat were generated. There was indeed a difficulty as to how the blood found its way to the left ventricle. We have seen that blood, according to Fabricius, was concocted in the liver and distributed by veins to the body. We also observed that the upper caval vein had a wide opening into the right auricle of the heart. Indeed, it seems to pass through and form part of the right auricle (fig. 25). From the right auricular chamber blood entered the right ventricle, and from there passed along a great channel—the pulmonary artery (fig. 26)—to enter and nourish the lungs. The difficulty came when Fabricius had to explain how the blood found its way from the right ventricle into that great brew chamber — the left ventricle. Between them there is a thick muscular wall or septum, with never a pore or opening to be seen in it. "That," said Fabricius, "was just as it should be"; visible holes were not necessary; sweat exuded from invisible pores of the skin, and it was by a process of sweating that blood passed from the right to the left ventricle.

Thus, having shown how air and blood reach the left ventricle, Fabricius proceeded to show how the hot vitalised blood thus formed was made to ebb and flow throughout the body. One had only to place a finger on the artery of the wrist to know that arteries expanded or went into a state of diastole, and then contracted or went into a state of systole seventy to eighty times a minute. They were expanding pumps which sucked the vitalised blood into the tissues of the body and then contracted and forced the blood backwards to the centre of the body again. It so happens, as we now know, that when the heart contracts its apex, resting against the front wall of the chest, can be felt to press forwards as if it were then expanding or in a state of diastole—as indeed Fabricius thought it was. He therefore had no difficulty in con-

vincing his audience that the blood in the arteries and heart was in a continual state of ebb and flow. The heart and arteries expanded at the same time ; any member of the audience could convince himself of that fact by feeling the impulse of a patient's heart with one hand, and the pulse at the wrist with the other. The heart and arteries expanded and drew the blood into the tissues. There it became laden with sooty vapours. Then the arteries and heart contracted, forcing the blood back

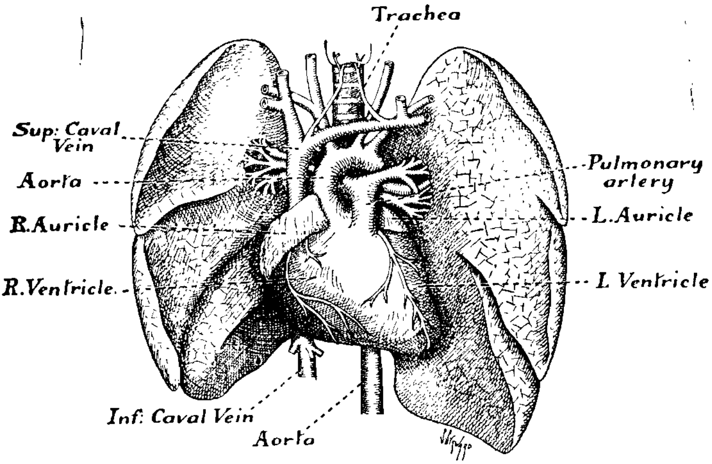


FIG. 26.—A diagram to illustrate what Harvey was taught concerning the use of the heart.

towards the central parts of the body, the fuliginous or sooty vapours being expressed from the heart into the lungs, and the blood was thus cleansed. The blood ebbed and flowed seventy or eighty times a minute. To ebb and flow was a law of Nature. The waters of the sea ebbed and flowed ; so did the breath, and so therefore did the blood.

Thus did Fabricius expound his argument to the audience of which young Harvey was one. There did not seem a single flaw in his reasoning; the human machine was consistently explained—why it had blood, veins, lungs, a heart and arteries, why the arteries could

be felt to expand and then contract, why the body was hot and how it was endowed with life. We may rest assured that his hearers went their ways and remained easy in mind when they applied the teaching of Padua in the treatment of their patients. All except the quiet, retiring Englishman. In the next chapter we shall see how certain doubts arose in his mind and how, adopting the methods of inquiry he had learned from Fabricius, he discovered that the heart was a double pump designed for driving the blood from arteries to veins and thus round and round the body. It was with Harvey, we shall find, as with every great discoverer; it is easier to make a discovery than to succeed in convincing one's fellowmen that one has been made.[1]

[1] For further details see *The Discovery of the Circulation of the Blood*, by Dr George Singer. (London: 1922.)

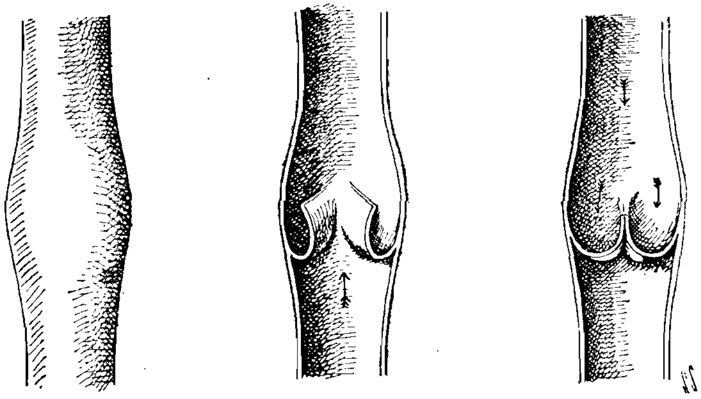
CHAPTER XI

HOW HARVEY DISCOVERED THAT THE HEART IS A DOUBLE PUMP

It so happened that during the two years which Harvey spent in Padua, Fabricius was making an investigation of the very strange trap-doors or sluice-gates which are set within veins. Some of these are depicted in fig. 27. Fabricius showed his pupils that these sluice-gates or valves were to be found at short intervals throughout the veins of the legs, arms, and also in the veins at the root of the neck. They were simple contrivances, being merely a pair of minute, very delicately made watch-pockets placed opposite each other within the vein. There was one feature about these contrivances on which Fabricius laid emphasis ; the mouths of the valve-pockets were always directed towards the central part of the body —towards the liver and heart. Their mouths were so set as to catch the tide of blood as it flowed outwards in the veins to nourish the tissues. Clearly, said Fabricius, the parts which hang downwards like the legs and arms would drain the blood from the central parts of the body if their veins were not specially guarded. But Harvey had noticed that the veins which *ascend* to the head also had valves, and that observation set him thinking.

Harvey was back in London in time to see the obsequies which followed the death of the Great Queen and the pageants which marked the arrival of the first Stuart king. Presently we find him a young married man practising as a physician in the city of London—his house being in Knightrider Street. Now, a young doctor waiting for

patients has time to spare, and this Harvey determined to devote to settling certain doubts which had arisen in his mind during the time he dissected and studied in Padua. Mark the way he proceeds to settle his doubts! He sets aside one of the rooms of his house for dissections—the dissection of animals, for at that time the human body itself was but seldom opened. He knew that the bodies of warm-blooded animals were constructed on the same plan as the human body. Hence he set to work and



A. B. C.

FIG. 27.

A, A swelling on a vein indicating the presence of a valve within it.
B, The vein laid open, showing the valves partly open.
C, Showing the valves shut.

dissected all kinds of animals. He looked very carefully at the valves of the veins and found them to be effective traps, shutting instantly when a current of blood or of water was made to flow outwards—the direction which Fabricius thought the blood took in life. He made the veins of his own arm swell by tying a ligature round its upper part; when he milked these swollen veins towards the hand he noticed that the blood refused to pass a valve; the valves were competent in living as well as in dead veins. He saw that the valves were set so as to allow the blood to pass in but one way—towards the

heart. This explained, too, why the valves in the veins of the neck were set with their mouths downwards—towards the heart. The veins therefore could not be channels for conveying blood outwards to nourish the tissues, as everyone then believed.

What, then, were the valves of veins for? The valves led towards the heart; it, too, was hung with valves. He set himself to study how they were set and shaped, and how they worked in the hearts of all kinds of animals. A very ordinary belief served as a magnetic needle to guide him in his inquiries. It was simply this: Nature is a perfect designer, and therefore every part of the human body and animal machine had been given the shape that best fitted it for the work it had to do. Shape was a clue to function. If we could not explain every etaild of a part of the human body, then we had not found out its true use; that was the touchstone Harvey applied to the structures in the human body. The manner in which the valves of the heart were set guided him as to the direction in which the blood must flow. Even then he was often puzzled to find an explanation for the use of certain parts of the heart. So he watched it at work while it was still living, and after observing hard for fourteen years was at last able to explain the use of its various parts. It turned out to be a more wonderfully contrived pump than any yet conceived by the inventive brain of man.

We can best understand what Harvey discovered in these fourteen years of studious inquiry if we attend the College of Physicians in London in 1616 and listen to him as he gives his first course of anatomy lectures. The college now looks out on Trafalgar Square, but in Harvey's time it was hid in Amen Corner, near St Paul's. The lad we saw set out from the King's School, Canterbury, has grown into a man of slight build with a quiet courteous bearing, a delicately cut, studious countenance, bearded in the Jacobean manner, a man taking his subject—but not himself—seriously. He is 37 years of age, has married a daughter of the king's physician,

and is himself now a physician to the great hospital of the City of London—St Bartholomew's. The lecture-room of the college in which we are to listen to him is small, but filled with a goodly company of learned physicians who are to see the foundation-stones of their most sacred beliefs crumble into dust as the lecturer proceeds. We find him showing the arrangement of valves in the veins; they are sluice-gates which permit the blood to flow in only one direction—towards the heart. That the blood does flow so can be proved by tying a living vein; the blood becomes dammed up not on the near side, but on the distant side of the ligature. The blood then is guided towards the right chambers of the heart—the auricle and ventricle. These chambers are opened, and Harvey shows that the passageway between them is guarded by a valve of a curious kind, quite unlike any fitted to ordinary pumps (fig. 28). The valve has to fit an opening or gateway which is always changing in size and shape, and therefore is made up of three parts or cusps which can be made to fit a passage of varying size. The cusps are small triangular sheets or sails of a tough flexible material, with their pointed ends hanging free in the chamber of the ventricle, while their broader ends are fastened to the margin of the auriculo-ventricular passage. The pointed parts of the cusps are tied to the wall of the ventricle by a number of cords—as if the cusps were sails and had been fastened in place by fairy sailors. The chief strings or stays, however, are not fastened directly to the wall of the ventricle, but to finger-like projections which rise up to meet them. These muscular fingers act as engines which can tighten or loosen the cusps or sails according to need. Harvey showed his audience that when blood entered the right ventricle the cusps or sails became bellowed out, and thus blocked the passageway so that the blood could not return to the right auricle. He could not believe, he said, that Nature had set up this elaborate contrivance at the passageway between the right chambers of the heart for no purpose. For him it was a valve, and a valve was a signpost which

told the direction in which the current of blood flowed ; it could flow only in one direction, from the auricle to the ventricle.

There was no need for Harvey to remind his audience that there are no visible pores or passages between the two ventricles ; that was admitted by all. It was also

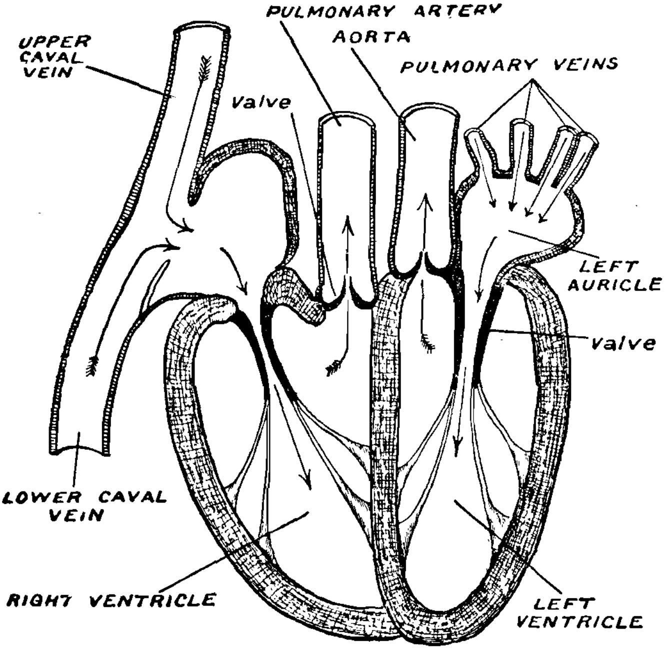


FIG. 28.—A diagram to show the four chambers of the heart and the valves which guard their openings.

admitted that the right ventricle had only two openings. One of them he had just described ; the other led into the great channel for the lungs—the *pulmonary artery* (fig. 28). He showed them that when the blood entered this channel it could not flow back into the ventricle, as they supposed it did, because the passageway was guarded by a valve which closed automatically and prevented a reflux. The valve at the pulmonary opening is made up of three membranous pockets, similar in construction to

the pocket valves of veins (fig. 28). The mouths of the pockets are set so as to catch a back flow; they fill instantly, with the result that their sides come together and block the passageway. Here again Harvey asked why a channel which was supposed to allow the venous nourishing blood to ebb and flow to and from the lungs should be guarded by pocket or semi-lunar valves which permitted a current to flow in only one direction—towards the lungs.

Harvey then told what he had succeeded in making out by watching the movements of the right chambers of the living heart. He confessed that at first he was much puzzled; so quick and obscure were their motions. By close observation he saw that the first movement was in the auricle, which became smaller and discharged its blood into the ventricle; it acted as a loading-pump. Then the right ventricle drew itself together, became smaller and discharged its load into the channel leading to the lungs. It acted as a force-pump—one of a peculiar kind. These movements followed so quickly on each other that it was hard for the eye to follow and make them out aright.

Now, the physicians who listened to Harvey knew very well that the lungs received two sets of vessels from the heart. There were first those which came from the great channel leading from the right ventricle; they had thick walls just like arteries, but as they conveyed venous nourishing blood, they looked on them as veins. Then there was the set of four big vessels which also conveyed blood from the left auricle to the lungs; they had thin walls like veins, but as they contained arterial blood, they looked upon them as the arteries of the lungs. They were quite well aware when all of these vessels were followed into the lungs, no matter whether they came from the right side or the left, that they branched and rebranched until they finally ended in vessels of the smallest size. But no one had ever seen communications between the two sets of terminal vessels, by which blood could pass from one set to the other. Yet Harvey insisted that

such through channels must exist. His hearers had not forgotten that a very clever Swiss, named Servetus, had also taught the same doctrine. Harvey boldly proclaimed that the right ventricle was a pump for forcing the blood through the lungs to the left side of the heart, because in no other way could an explanation be given of the construction of the chambers, valves, and channels of the right side of the heart. He pinned his faith on the unerring skill with which Nature builds her machines. There were no superfluous parts in her constructions; every one had its use and meaning.

There never was a more complete argument than the one which we are now following as Harvey unfolds it. As was the custom at that time, he held a silver-tipped wand in his hand and used it to point out the structures concerned in his discourse. Turning to the left chambers of the heart, he asked his assistant or demonstrator to lay them open. He asked the spectators to note that the mouths by which the vessels of the lungs—the pulmonary veins—opened in the upper or auricular chamber were free and unguarded (fig. 28). On the other hand, the passage from that chamber to the left ventricle was guarded by a stout valve constructed on the same plan as on the right side—except that its funnel-shaped part, hanging within the ventricular cavity, was divided into only two cusps, like a bishop's mitre. The cords of the cusps ended, as in the right side, by being attached to muscular engines projecting from the wall of the cavity and acting as if they were miniature sailors hanging on the stays of wind-filled sails. His audience was willing to agree with him that the passageway between the left auricle and ventricle was competently guarded, and that the blood in the left ventricle could not flow back towards the lungs when that chamber contracted or went into a state of systole. On the other hand, his hearers maintained that although the blood could not go back, yet the sooty fumes brewed in the blood certainly could and did. "Good God!" exclaimed Harvey, "how can a valve prevent one and not the other?" The blood having reached the left

ventricle, causing the cusps to bellow out and thus automatically shutting the main doorway of the chamber, had only one passage open for its exit—that leading to the aorta. That opening, Harvey pointed out, was efficiently guarded by three semi-lunar or pocket valves, which allowed free passage from the ventricle. The moment the blood in the aorta sought to flow backwards, the pockets filled, their edges came together and the passage became tightly closed. The more the column of blood in the aorta pressed backwards, the tighter were the edges of the pockets pressed together. There could, therefore, be no ebb and flow of the blood to and from the left ventricle ; it must pass always in one direction—towards the mouth of the aorta.

As usual the valves served Harvey as finger-posts. He hastened to explain that he had not been content to merely guess the meaning of the signposts ; he had watched the heart at work. He described the immense effort made by the left ventricle when it contracted ; it became blanched and erect, its apex coming forwards. At the very moment of action, when the apex of the heart could be seen and felt to project, the aorta expanded and became more turgid. He observed that the contraction of the left auricle immediately preceded that of the ventricle ; the auricle was clearly a pump for loading the ventricle. Then the left ventricle contracted and emptied its load into the aorta. All these events followed so fast, sometimes too quickly for the separate beats to be counted, that it was difficult to be quite certain of all that happened. He described how he proceeded to make certain that the heart was acting as a pump. He pricked the great vessels into which the ventricles pumped their loads ; the spurt which issued became heightened with every stroke of the ventricles. He tied the great arterial channels with ligatures ; the ventricular chambers became engorged, while the pulmonary artery and aorta became emptier. He tied the great veins leading to the heart ; immediately they became distended, while the heart became empty. He tied a small vein far away from the heart,

it became swollen beyond the ligature; he opened an adjacent artery, the blood spurted with each beat from the end next to the heart.

Then Harvey approached the crisis of his argument. He found that the left ventricle of a man's heart held 2 oz. of blood, without being at all distended, but in order not to exaggerate the work that the heart performed as a pump, he counted on only half the load being discharged at one stroke. Now, if the left ventricle discharges but 1 oz. into the aorta at each beat, and beats at seventy times a minute, then in 10 minutes it will have discharged 700 oz.—35 pints of blood,—which is not only more than the aorta and all the arteries could hold, but two or three times more than would fill all the vessels of a man's body.[1] He was certain of his facts, certain that every part of the human machine was shaped to serve a definite purpose. What, then, became of the blood pumped into the aorta? How was it that the veins were kept so constantly filled? There was only one possible explanation, he maintained, and that was that there must exist channels or pores between the arteries and the veins, and that the blood must flow in a circle from arteries to veins. The heart was, therefore, a double pump which kept up the circular flow of blood. Harvey saw these pores or communications only with the eye of faith; not one of his hearers believed that such passages existed.

These were famous lectures which Harvey gave in 1616 at the College of Physicians of London. He became the King's physician. At the battle of Edgehill he sat under a hedge with the royal princes watching a royal progress which led towards the scaffold. He remained all his life long a patient, careful student of living things, dying in 1657—during the days of the Commonwealth—in his 78th year. Four years after his death Malpighi, a great Italian anatomist, by means of the microscopes he had learned to use, saw the channels which actually lead from the arteries to the veins—the channels which Harvey knew of although he had never seen them. They have exceedingly delicate transparent walls, and

[1] See Appendix F, p. 295.

are so narrow that the red blood discs have to pass along them in single file. Time has shown that these fine channels or capillaries are the vessels which irrigate and nourish the tissue-fields of the body; the arteries are the pipes or viaducts conducting the blood to these fields; the veins are merely the canals which Nature, ever economical in her contrivances, uses for bringing the blood back to the central pump—the heart. The capillary network is the essential part of the vascular outfit of the body. Harvey never saw the capillary field, but it was his discoveries which gave us the key that unlocked its secrets. Harvey made the merest tyro in medicine wiser than the most renowned of ancient physicians.

When we look beneath the surface of things we see a similarity in the triumphs of Columbus and of Harvey. Columbus, from a survey of facts, became convinced that the earth was a sphere; no other theory could explain the facts. If the earth was a sphere, then it was possible to reach the Indies by sailing westwards as easily as by sailing eastwards, the route discovered by the Portuguese. On the strength of that belief Columbus followed the setting sun across the Atlantic, and had the courage to keep on when all his companions wanted to turn back, and thereby discovered for Europe a new continent. From an examination of valves and a study of the flow of blood in the vessels Harvey became convinced that there must exist communications between arteries and veins, and thereby he gave the world of learning a new continent of knowledge.

I have compared Harvey to Columbus, but there is another man—named by his creator Sherlock Holmes—with whom he may also be compared profitably. For a real man of science like Harvey is a detective—a detective of Nature's secrets. There was a day, the reader will remember, when Sherlock Holmes, sitting in his rooms in Baker Street, surprised a friend by accusing him of having been at a certain post-office and having sent off a telegram to a certain person. The explanation

of the detective's power of second sight, you will remember, was quite simple. There was clay on his friend's boots, which could have come only from a drain which had been opened outside the door of a certain post-office, and there were other facts which could only be explained if a telegram to a certain person had been dispatched from that post-office. Sherlock Holmes had noted a number of facts and sought to explain them by making a guess which would make all of them fit together. There was only one guess which could explain all of them. Such a guess the man of science calls a theory or hypothesis. Only Sherlock Holmes was so certain of his explanation that he stated it as a fact, not as a guess. Harvey set to work in the manner of a Sherlock Holmes ; he patiently collected facts for a long series of years, and sought for a guess which would explain all of them, and found it—the circulation of the blood. Men of science are only superior detectives after all !

CHAPTER XII

HOW A "HEAD OF PRESSURE" IS MAINTAINED IN THE ARTERIES

We have seen that the muscular engines of the body are permeated from end to end with a network of fine capillary vessels. From this network countless cylinders of the muscles are fed with fuel and oxygen. We have also seen that all the levers of the body are traversed by a similar system of fine blood-vessels from which the bone-builders draw material for their sustenance and work. Indeed every organ of the body—the brain, liver, stomach, skin, and the heart itself—is really a spongework of capillaries with the living units or corpuscles built within the exceeding fine interstices of the meshwork. If we could wash out all the living units from a man's body and yet preserve the capillary network—as the rain sometimes does to withered leaves—we should have before us the complete outline of a man made up of a network of vessels so minute that we should require a microscope to detect the meshes. We should see in such a sponge-like spectre of a man the arteries branch and rebranch until they ultimately ended in the capillary field of vessels; we should see the veins begin on the edges of the field as exceedingly small vessels, which unite and reunite until the large channels leading towards the heart become formed. We are now to see how the heart maintains a constant flow of blood throughout this vast capillary field. We cannot prick the living body anywhere without drawing blood, showing that the flow is everywhere, and that it never ceases; no matter which artery we wound, the

blood spurts out; blood is being pumped into it all the time.

An engineer who has to think out a method of providing the inhabitants of a hill-set city with a constant supply of water knows something of the difficulties which Nature had to overcome before she could succeed in providing each living unit of her complex machines with a constant supply of blood. A head of pressure has to be maintained so that the flow of water or blood may be constant and plentiful. The water-engineer may employ, as Nature had done before him, a pump to force the water up to the required level; nor does the plan of the pump he adopts differ in essentials from the one worked out by Nature in her master-pump—the heart. In fig. 29 a force-pump of a simple construction is compared with the main pump of the body—the left ventricle. In both there is an inflow pipe conducting to the main-pump chamber; only in the human pump the inflow passes through a loading chamber—a contrivance which, as far as I can learn, has never been fitted to a pump made of metal or of wood. As the inflow enters the main chamber it passes an inlet valve, a simple trap-door contrivance in the water-pump, but an elaborate arrangement of sail-like cusps in the blood-pump—forming the mitral valve (fig. 29). From the main chamber opens the outflow pipe—guarded by the outlet valve—again a simple trap-door contrivance in the water-pump, but a triple pocket valve in the blood-pump (fig. 29).

The arrangement of valves is the same in both kinds of pump, but the manner in which the contents are forced out from the main chamber is quite different. In the water-pump a rigid piston descends within a metal cylinder, and thus obliterates the space of the main chamber and forces the water through the outflow pipe, past the outlet valve. The power or strength which drives the piston or plunger is obtained from an engine which is placed at some distance from the pump. In the heart there are no separate plungers or pistons; every part of the wall of the main chamber moves inwards, as if it formed part of a

universal piston. The entire wall moving inwards, thus drives the blood from the left ventricle through the outlet valve into the aorta. The engine which works the ventricular pump is not set up some distance away, but is actually built into its walls. The thickness of the

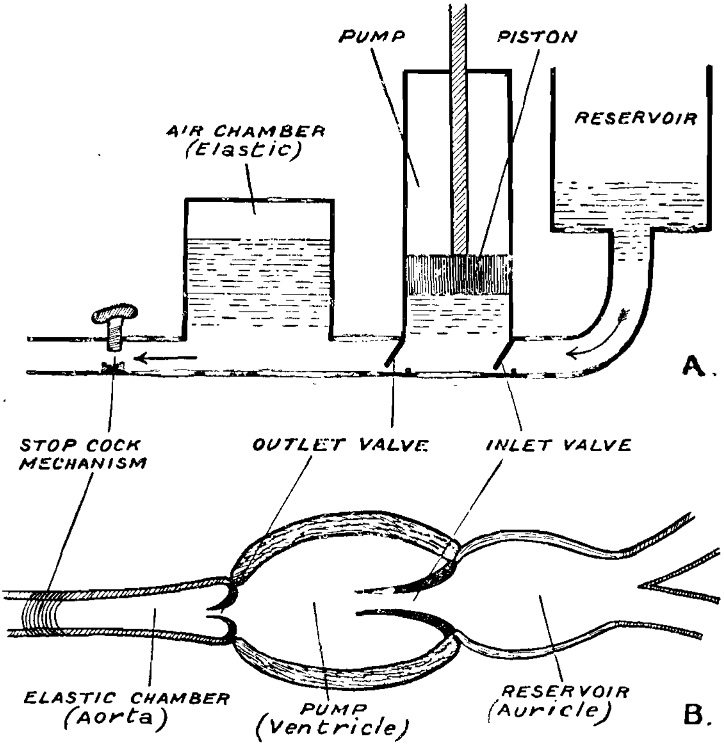


FIG. 29.—The various parts of a force-pump (A) compared with the parts of the left ventricular pump (B).

wall of the left ventricle represents a muscular engine, one made up of countless microscopic cylinders of a rather peculiar kind, differing somewhat from the cylinders of body muscles. The total weight of the muscular engine which expels the contents of the left ventricle is just under a quarter of a pound in a person whose body-weight is 110 lb. These figures are based

on very careful measurements made in London by Sir Thomas Lewis.[1] The muscular wall of the left ventricle varies in thickness according to the state of contraction and the part of the wall which is measured, but we may look upon half an inch as a common amount. The problem of grouping tens of thousands of contractile cylinders in the wall of a pump, so that each of them can exert its full power in forcing the blood from the pump chamber, taxed the ingenuity of Nature to its utmost. The difficulty is at once manifest when we take in our hand a hollow thick-walled india-rubber ball filled with water and try to empty it by compressing the thick wall with our fingers. The compressing fingers represent the muscular wall or engine of the ventricle; we find it impossible to squeeze the ball uniformly, and thus force out its contents by obliterating its cavity. Yet Nature, using a ventricular chamber which is half an inch thick or more in some parts, succeeds in bringing the walls uniformly inwards so that the cavity is obliterated and practically the whole pumpful of blood discharged. This she has succeeded in doing by arranging layers of muscle cylinders in overlapping spirals, with the result that when they contract they move inwards, much in the same way as the segments of the iris diaphragm, used by photographers, move inwards on each other until only a pin-hole aperture is left. Thus the left ventricle is a very remarkable kind of pump—one with walls built out of the engine which actually sets it in motion, and in this way drives the blood onwards.

There is one defect which all force-pumps have: their outflow is jerky or intermittent. Engineers have overcome this defect by adopting a very simple contrivance. The outflow pipe (fig. 29) leads to a closed chamber which contains air in its upper part. The pipe leading from the air chamber is fitted with a stopcock so that the water may not flow away from the air chamber as quickly as it enters from the pump. Each stroke not ly forces a pumpful into the air chamber, but also com-

[1] *Heart*, 1914, vol. v. p. 367.

presses the cushion of air which thus stores up part of the strength of each stroke. The air in the chamber becomes a compressed elastic cushion. The water in the air chamber being thus maintained under a steady pressure flows continuously, instead of in jets. Nature overcame the intermittent outflow from the heart, not by using an air chamber, but by constructing a chamber with elastic walls. The aorta stands for the air or compression outflow chambers; its walls are made of a remarkably elastic material. Part of the strength of each stroke of the heart is spent in expanding the aorta; at the end of the stroke the recoil of the aortic wall presses the blood onwards and thus maintains a steady flow between the strokes of the heart. In the arteries, particularly in the smaller arteries, the elastic coat is strengthened by another containing muscular tissue. The elastic tissue of which the wall of the outflow or aorta chamber is composed is unfortunately a very delicate material, and even by the age of 40 it has usually lost its perfect elasticity. Hence after 40 the work of the heart is harder; its outflow box is less resilient, less able to help the onflow between the pump strokes.

In order to maintain a steady flow of blood through the capillary fields which permeate the length and breadth of the entire body, it is clear that a high head of pressure must be maintained in the compression or aortic chamber of the human pump. Harvey estimated the amount of blood which the heart throws into the aorta in a given time, but he made no attempt to find out the head of pressure maintained in the aorta. That was measured a century after Harvey's time by a country clergyman named Stephen Hales—a natural philosopher of the most lovable and ingenious kind. He tied a glass tube into an artery which sprang from the aorta of an aged mare, and holding it upright noticed the height to which the blood rose. If this experiment could be made in a young man in good health, the column of blood, as we have learned in another and less painful way, would rise 64 inches (160 ctm.) above the level of the heart.

This is the head of pressure maintained in the aorta or compression chamber by the human ventricular pump. If the head of pressure falls below 24 inches, then the force in the aorta is not sufficient to keep up a flow through the capillary fields of the body, and death soon follows. Our life and health depend on the aortic head of pressure.

We must now examine for a moment the mechanism by which a head of pressure is maintained in our arteries, for there is no need to emphasise how important this matter is for the welfare of the entire machinery of the human body. We have only to look at the compression chamber attached to the simple pump in fig. 29 (p. 110) to see that the head of pressure may be altered in two ways: (1) increasing the inflow by speeding up the pump, or by giving the piston a greater length of stroke, or by both means; (2) diminishing the outflow by turning the stopcock still further off. Pressure will be diminished by turning on the stopcock more fully or by slowing the action of the pump. It will also be noticed that the head of pressure is no indication of the amount of fluid passing through the compression chamber; if the stopcock of the outflow pipe be nearly closed, then a very slight inflow from the pump will maintain a high head of pressure. Now Nature uses both of these means for regulating the head of pressure in the arterial compression chamber of the human body; the strokes of the heart may be increased or diminished in number or in volume or in both. She has established the most elaborate system of stopcocks, which can be turned on or off to any degree. By these means the head of pressure in arteries can be regulated to the exact needs of the machine.

The heart is thus a muscular engine-pump. We have seen that when all the muscular engines of the body are in action they must be supplied with seven or eight times the amount of fuel and oxygen needed while in a state of rest. When the body is in action, then, the heart has to pump at a much greater rate. Physiologists estimate that

when a man is sitting quietly his left ventricle throws about 3 litres (5 pints) of blood into the aorta every minute ; a heart going at the rate of seventy beats a minute and throwing out 42 c.c. ($1\frac{1}{2}$ oz.) per stroke will accomplish this amount. If the man gets up and sets out walking at four miles an hour, then the output of blood becomes four times as much ; if he runs upstairs the output becomes seven times as much—namely, 21 litres (37 pints) per minute. The total amount of blood in a man's body is about 5 litres (8·8 English pints), thus four times a minute our left ventricle has forced the whole of the blood in our body through the aorta once and begun on a further turn when we take violent exercise.[1] But how is it that the muscles succeed in making their wants known to the heart? How do they compel the heart to increase its output according to their needs? The muscular engines of the body are started and stopped by higher centres in the brain—the seat of will, but the will has no power over the heart ; the upper centres of the brain which control the muscular engines of the body have no power to start or stop the heart. The impulse that sets the muscular engines of the heart in action arises within the musculature itself. For although the heart receives no nerves from the higher or voluntary centres of the brain, it is most richly connected with a lower centre or nerve exchange situated in the medulla. Into this centre stream nerves from the heart itself—particularly from the left ventricle ; and from the aorta, which represents the compression chamber of the heart. By means of these nerve paths messages are being conveyed to the medullary centre which give information regarding the state of tension in the pump and the head of pressure in its compression chamber. From the medullary centre or centres stream out at least two sets of nerve paths to the heart, by means of which the strokes of the pump can be increased in number or extent or both. By some means which we do not rightly understand, the voluntary muscles can influence the work of the heart through the medullary nerve centres. But there must be another

[1] See Appendices B, p. 276, and F, p. 295.

way, for after all the nerve paths to the heart were cut, Professor Starling found that the heart still responded if increased work were thrown on it. The greater the volume of blood that entered it, the more did its main chamber expand and the stronger grew the force of its stroke. There is a degree of filling and expansion of the main chamber at which the heart-pump works best. Now, when the muscles of the body are set in action their movements force blood along the veins towards the heart, thus filling it more quickly and to a greater extent than before. In this way muscles can set the heart at work. The musculature of the heart at once responds to the increased load of blood just as an overladen horse does when it has to breast a hill. The very words I use to explain this remarkable faculty of response which is inherent in the heart show how much we have still to learn concerning the wonderful mechanism of the heart.

It is when we turn to the stopcock contrivance that we get most light on the machinery by which the muscles of the body control the work and output of the heart. In fig. 30 a drawing is given of a vascular stopcock; superficially it has no resemblance at all to the form which we are familiar with in water-taps, yet it serves the same purpose as stopcocks which regulate the flow in water-mains. A small artery is seen ending in a microscopic part of the capillary field (fig. 30); the artery has muscular fibres set as circles or spirals in its wall; they are minute spindle-shaped fibres which can be made to contract and thus constrict, even close, the artery; they can also be made to relax, and thus permit the artery to dilate and allow blood to flow more freely. These cuffs of muscular fibres represent stopcocks; they regulate the outflow of blood from the arterial compression chamber of the cardiac pump. The higher centres of the brain have no control over them; they are entirely managed by nerve centres in the spinal cord. As these terminal arteries number tens of thousands, and each of them is regulated and controlled, one can perceive how complex the stopcock system of the human machine is.

A single muscle, like the biceps, has two or three hundred terminal arteries, and each has its constrictor muscle or stopcock. When the biceps is set in action, the arterial stopcocks are also turned on. Every muscle or organ can somehow command its vascular supply—can have its turn-cocks turned on and off. We are not certain how a muscle succeeds in getting access to the nerve centres which control the stopcocks ; we simply know that it is so. In walking or in hard exercise like digging, when all the muscles are in action, it is plain that half or more of the vascular stopcocks of the body must be turned on full, and that the head of pressure in the aorta will quickly

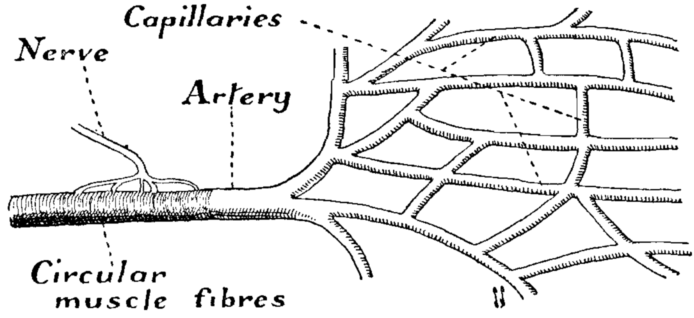


FIG. 30.—A terminal artery, surrounded by muscle fibres, ending in a network of capillary vessels.

fall unless the heart responds by increasing its output. We know that the heart always responds ; it can increase output to eight times or more the amount thrown out when the body is at rest.

There is, however, another mechanism, besides that of increasing the output of the heart, which is employed to keep up the head of blood-pressure in the aorta. The terminal arteries leading to parts which are not required in severe bodily exercise, such as the organs of digestion and the brain, are constricted, thus economising the blood supply for the benefit of the muscles. When the muscles are set in motion their vascular stopcocks are turned on, while others are turned off. If the human machine were not supplied by this elaborate stopcock system, it would

be impossible, as Dr Leonard Hill has shown, to regulate the distribution of blood to the various parts of the body. Everyone knows how difficult it is to do head work immediately after a meal. The stomach and organs of digestion have then their vascular stopcocks turned full on; the needs of the stomach take precedence then of those of the brain. The brain, if it pushes hard enough, may obtain a blood-supply at the expense of that rightfully designated for the organs of digestion, but it is certain to have to pay for its greed sooner or later by headache. Every time we alter our posture—when we lie down, stand up, or sit upright—there is a silent and automatic switching of the tens of thousands of vascular stopcocks of the body. We are so unconscious of this silent activity that we find it difficult to believe that it actually occurs. A moment's reflection will show that this switching on and off must take place. When we rise from bed in the morning our feet and legs, were it not for the automatic turn-cocks, would draw all the blood from the head, for they have the advantage of gravity. Our hands would be engorged, while our shoulders would starve for blood; the organs in the upper part of the body would bleed into those in the lower part. The moment we stand up the vascular controlling centres in the spinal cord—being nerve exchange centres, receiving and giving thousands of messages of which we are unconscious—come into action and regulate the distribution of blood by turning off and on the vascular stopcocks of the body. This machinery may break down under certain circumstances, particularly after we have been kept standing in a hot stuffy room in a crowd of people. We may then have a sudden faint and collapse on the floor, because the vascular stopcock machinery has been overtaxed or broken down. The blood has been drained from the brain; hence the unconsciousness.

There is another wonderful mechanism brought into operation by the animal machine when an effort has to be made—a mechanism made clear to us in late years by Professor W. B. Cannon of Harvard University. It

would be too much of a strain on the nerve centres which look after the vascular stopcocks if they had to be in full action throughout a prolonged muscular exertion. Professor Cannon found that when we make up our minds to an effort certain nerve messages are dispatched to small bodies situated above the kidneys—the adrenal bodies. These nerve messages cause the adrenal bodies to throw into the blood circulating through them a substance or drug called adrenalin. This drug acts automatically on the muscular stopcocks of the arteries which supply abdominal organs, causing them to close down to a greater or less degree, thus setting more blood free for the use of the muscles. On the liver adrenalin produces another effect; it causes it to throw a form of sugar into the blood—the staple fuel of muscular engines. Thus by means of the adrenalin mechanism the muscles are given a more liberal supply of both blood and sugar. The mechanism is at work as long as an effort is made. The same mechanism is also set at work if we become angry or if we are placed in a position of peril. Those who have gone through the bombing which attended air raids will remember the tendency for the teeth to chatter at the onset of the attack, and the feeling of lassitude and tiredness which followed when the raid was over. Bomb-dropping makes a severe demand on the adrenal mechanism, and hence produces a feeling of exhaustion—as if we had made a great effort.

I have dallied over the inventiveness which Nature displays in obtaining a just distribution of blood to the various parts of the human machine. She has solved many problems which still tax the ingenuity of engineers who have to furnish great cities with a supply of water according to the passing needs of its inhabitants. We must return, however, to the comparison which we set out to make between a motor cycle and the human machine. It is true that the motor cycle has no separate pump which may be compared to the heart, and yet we can say, I think, that the motor cycle has a circulation. We have already seen the manner in which muscle

cylinders are supplied from the capillary field with the materials of a combustion mixture—oxygen and blood-sugar. The supply is carried into the cylinders by arteries, and the effete products are carried away from them by veins. It is the heart which circulates the blood in the capillary field and maintains the supply of combustion material to the muscular engines. When we examine the mechanism of a motor-cycle engine we find the circulation of a combustion mixture through its cylinder ; the petrolised air enters by the inlet pipe or artery and leaves by the outlet pipe or vein. That circulation is maintained by the movements of the piston ; it is drawn in by the suction stroke, and expelled by the exhaust stroke ; for two strokes in each cycle the engine acts as a pump or heart. Thus in the engine of a motor cycle we have a primitive condition—a machine which serves the purposes of muscle and heart combined. In the human machine we reach a much higher point of evolution—one where the driving power and circulating force are carried on by separate machines.

CHAPTER XIII

A PAIR OF LIVING BELLOWS

Often in former chapters, especially when describing the muscular engines and the heart or blood-pump of the human machine, we had occasion to mention how oxygen was carried to them by the microscopic red discs of the blood. If oxygen is withheld, the muscular engines and pump are not only disabled but cease to work almost immediately. So far not a word has been said of how the red blood discs come by their loads of oxygen. This is the subject upon which we now enter. Here again, we shall find that Nature has adopted a kind of machine which man has also discovered and used for many purposes, namely, the bellows. Our chest or thorax is really a pair of bellows; there is a windpipe or trachea, just as the bellows has an air-pipe; at the end of the pipe is fitted a nose or nozzle. The human pair of bellows are lined by two much-folded membranes—the lungs. Within the lungs, which line the thorax or bellows, are air chambers. It is from these air chambers that the red blood discs pick up their loads of oxygen.

We are so familiar with the movements of the bellows of the human machine that we never give them much attention. They go on by themselves morning, noon, and night; we have not to trouble about them, because they are managed for us. Even if we do try to stop or alter their actions, we have discovered long ago that their control is quickly snatched from us. With an effort we may bring our wills into action and stop them for sixty seconds or even more, but at the end of that time some

power stronger than our wills comes in and we have to let go our hold. Very early in life we notice that when we run hard, climb stairs, or lift heavy weights we breathe quicker and more deeply. Bit by bit we found out that our breath may be stopped by accidents of various kinds. We may be caught in a crowd and our bodies so pinned that we cannot expand our chests ; our chests are then in the same fix as a pair of bellows with its handles locked together. We may swallow something which is caught in the throat or we may fall into a pond or river ; breathing then ceases, because the passageway leading to the lungs is blocked. A pair of lungs with a choked windpipe are just as useless as a pair of bellows with a choked nozzle. If we hold the valve open which guards the window on the side of a bellows we find, when we work the handles, that the air no longer enters and leaves by the nozzle but by the large valvular opening on the side. Similarly, if a large opening should be made in the wall of the thorax, the breath no longer enters by the windpipe but by the new aperture. The lungs then become collapsed, and suffocation follows.

There are accidents in which we may be choked and yet the breath passages are not obstructed nor are the movements of the thorax prevented. This happens when men descend disused wells or mines and breathe foul air—air with an insufficient amount of oxygen in it ; they die of oxygen starvation.[1] Were we to use a pair of bellows filled with such air to blow up a fire, we should put it out instead of reviving it. There is still another way in which the human machine may be suffocated—one which cannot be illustrated on an ordinary pair of bellows. If for any reason the red discs cannot pick up their loads of oxygen from the air chambers of the lungs, then suffocation takes place. This may happen from many causes : the blood channels to the lungs may become blocked ; the great pump which drives the red discs along may fail ; or the discs may become laden with certain fumes, and therefore have no appetite for their regular diet of oxygen, as in coal-gas poisoning. All these things

[1] See Appendix G, p. 297.

we may know and yet never clearly perceive that the breathing system of the human machine is simply a pair of bellows—but bellows so marvellously constructed that we can find nothing even approaching them in perfection of workmanship among human inventions. They may work on continuously seventeen or twenty times a minute, day after day, for a stretch of seventy years or more. Unfortunately that is not always the case ; but we can say that when the bellows of the human machine break down the fault does not lie either in their workmanship or in their construction.

In quiet, dry, crisp, frosty mornings about Christmas time we can often see our breath breaking on the air as little wisps of steam, so like the puffs which issue from the funnel of steam engines that we may almost fancy that they too have a pulmonary system. But the ill-smelling fumes which shoot out from the exhaust pipe of a motor cycle never lead us to suppose that they are issuing from a true respiratory chamber. Even those who are most familiar with motor cycles never credit them with any part corresponding to a chest and lungs or suppose that they have a respiratory system. Yet I think we may say with truth that the engine of a motor cycle does breathe—does possess a respiratory mechanism. The diagrams of the movements of the piston, reproduced on p. 12, show that in the first stroke of a four-cycle engine the mixture of air and petrol vapour rushes into the cylinder to occupy the space left above the descending piston. The air rushes in because we human beings, like crawling crabs, live on the bottom of a deep and heavy sea—not of water but of air. Hence as the piston descends and leaves an empty space behind it the air rushes into the cylinder, carrying the petrolised air with it. The cylinder and piston represent a thorax of a peculiar kind ; the suction stroke of the piston constitutes the act of taking a breath—the act of inspiration. Then when combustion has taken place an upward stroke of the piston thrusts the burnt air from the cylinder out through the exhaust or outlet passage. The exhaust

stroke represents breathing out—the act of expiration. In the human machine air is taken in and given out at a rate of seventeen or twenty times a minute, but in the motor cycle respirations are much quicker; it may breathe a thousand times or more a minute and in a given space of time consume as much air as a hundred men.

The reader may very well raise the objection that the taking in and giving out of air is not necessarily the same as breathing. We may take a pair of bellows and close the side valve so that when we work the handles the air enters and leaves by the same passage—the nozzled pipe. The tide of air which thus flows in and out does not constitute breathing. The air is thrown out in the same state as when it entered the bellows; it is no warmer, it contains no more moisture, the proportion of oxygen is still the same—making up in round figures 21 parts in every 100 volumes of air. The air which we breathe out differs from that we breathe in in all of these three characters: it has become heated, it is laden with moisture, part of the oxygen has been combined with carbon, forming another gas—carbon dioxide, or as its discoverer, Joseph Black, named it in 1754, "fixed air." These are the characteristic changes which air undergoes when it has been breathed by a living machine like the human body. Now, the air which issues from the exhaust pipe of a motor cycle has undergone all of these changes: it has become very hot, it is laden with moisture, its oxygen has combined with carbon to form "fixed air." It is true that the motor cycle breathes in by one passage and out by another, while in the animal machine Nature, economical as usual, makes one pipe serve both purposes. The engine of a motor cycle, then, is provided with a respiratory system which is strictly comparable to the same system in the human machine with the additional advantage of being the more easily understood. Further, the internal-combustion engine of a bicycle may be suffocated. This happens if the piston becomes jammed, just as our thorax may be jammed in a crowd; suffocation

will also follow if the inlet passage is choked, which corresponds to an obstruction in the windpipe of the human machine. Similarly vitiated air which will not support the needs of the human body will also bring the motor cycle to a sudden stop. The more work we compel the human machine to do, the quicker it must breathe; the more air and oxygen must it consume. This is also true of the engine of the motor cycle. When tested in all of these ways we thus see that a series of movements, which may be named respiratory, do go on in the internal-combustion engine of a motor cycle.

We have already laid open the cylinder of the engine of a motor cycle and seen its respiratory chamber and the manner in which air is drawn in and forced out (fig. 1). We are now to lay open the respiratory chambers of the human machine—in order to examine the air passages and the parts which serve to set the sides of the bellows in motion. The most instructive view is got when the thorax is laid open from the side, and as the man depicted in Plates I. and II. has turned his left side towards us, we shall make our approach from this side. Our first aim is to see the machinery employed in expanding and contracting the bellows' wall. Before that can be done a most severe surgical operation has to be performed—the left arm and shoulder have to be removed in order that the upper part of the wall of the thorax can be displayed. The shoulders not only hide but actually rest on the upper part of the respiratory bellows, which at first sight appears a bad arrangement, for their weight must clog respiratory movements. We have already seen how Nature has overcome this difficulty by suspending the shoulders by living muscular straps or engines which come into action when we sit up or stand (p. 25); but all of us know that the shoulders have to be lifted or elevated when a deep breath is taken. Nay, if these suspending engines become weak or lazy from inattention and the shoulders are allowed to droop or slope, then the upper part of the respiratory bellows is pressed upon and rendered almost useless.

When the left arm and shoulder are cleared away the side wall of the thorax is laid bare from the neck above to the loins below. We note that from top to bottom the wall is strengthened by ribs—a series of bent bony levers of a remarkable kind. These levers are arranged in a definite order; they become longer as one passes from the 1st to the 8th, and then shorter until the 12th is reached, which may be no longer than a little finger. When the body is in the upright posture not even the first rib is horizontal; all of them, as they pass towards the front of the body and the breast-bone, slope downwards to a greater or less degree, the downward slope increasing as we descend the series. We may dismiss the two last ribs of the series—the 11th and 12th—from our consideration now, for they take only an indirect part in expanding the thorax. They end abruptly, after passing forwards for some distance, in the muscles of the body-wall. When a breath is taken these two ribs remain stationary or may actually move downwards, whereas the other ribs swing upwards. All the ribs, except the two last, when they reach the front wall of the thorax undergo a sudden change in substance; bone is replaced by gristle or cartilage—a material which has the springiness and elasticity of cane and gives a resiliency to the thoracic bellows. By means of these cartilaginous continuations the upper seven ribs are attached directly to the breast-bone, thus forming half-hoops; we may regard the breast-bone as forming a small part of the load which the rib-levers have to lift when they swing upwards in the act of inspiration. The 8th, 9th, and 10th ribs also help in this act, for although their cartilages do not directly reach the breast-bone yet they do so indirectly, for the cartilage of each turns up and joins the one directly above it, and thus all help to support and lift the breast-bone in front.

In this way the lateral wall of the thoracic bellows is strengthened and made movable by the insertion of a series of bent levers. There is no need to study the whole series of ribs; if we know about the mechanism of one of them, we understand that of all. The 7th rib will

answer well as an example for study ; the 7th rib and its companion the 8th are the longest, strongest, and most important of the series (fig. 31). In our study of levers we found three points which required attention : (1) the

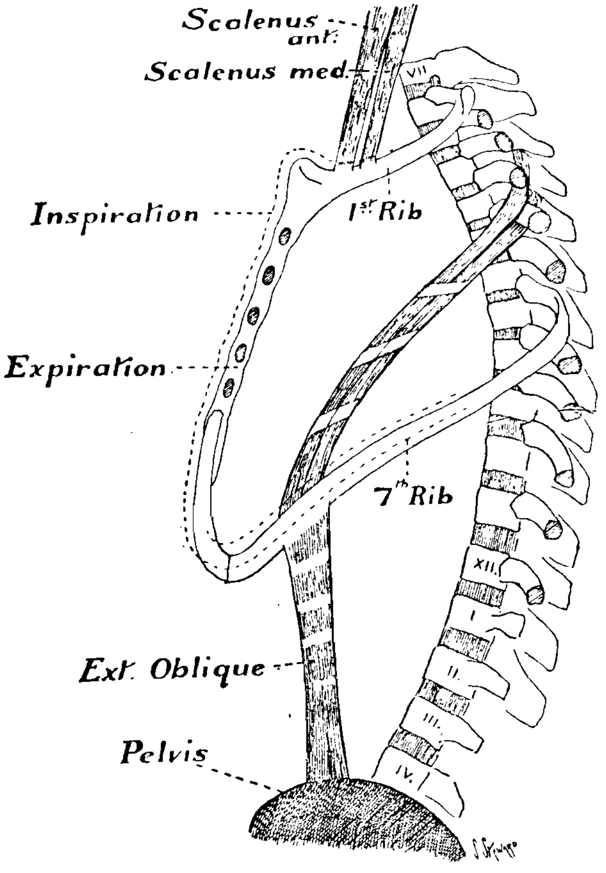


FIG. 31.—To show the manner in which the 7th rib and the muscular sheets attached to it (only parts of which are shown) help in expanding the thorax.

fulcrum or hinge on which the lever works ; (2) the muscular engines which move it ; (3) the load which has to be lifted, or the resistance which has to be overcome. We are dealing, as far as ribs are concerned, with levers of the third order—the forearm being the example of that order,

which we have already looked at. In the forearm the hinge or fulcrum is at the elbow-joint ; the weight is placed in the hand ; the engines which work the lever are the two brachial muscles—one placed in front of the arm, the other behind it (fig. 7, p. 42). The 7th rib also has its fulcrum, its engines and load. The backbone serves as its fulcrum, but the attachment is of a peculiar kind—one which has not been rightly explained before. The whole of that part of a rib-lever which is situated in the back of the body forms a fulcrum or axis round which the front end of a rib is raised or lowered. The hinder end of the 7th rib is held in position, firstly, by ligaments which tie it to the backbone ; secondly, by the muscles which keep the spine erect; they are attached to the hinder segment of the 7th rib—as to all ribs—in such a way that they fix it and maintain it in position when the front part of a rib is ascending or descending. Thus muscular engines are actually employed in holding or balancing the axis on which a rib turns.

Having seen how the 7th costal lever is joined to the backbone, we turn to examine the engines which make it move so that it expands and compresses the respiratory bellows. In fig. 31 part of a sheet of muscle is represented as rising from the backbone and passing forwards and downwards to catch hold of the 7th rib. This is part of the muscular engine which raises the rib ; the backbone is the fixed base from which it pulls. But it will be noticed that certain lines cross the sheet of muscle thus depicted (fig. 31) ; these are to indicate that in reality the muscular sheet that lifts the 7th rib is interrupted—is broken into short intercostal segments—by the ribs immediately above the 7th. These ribs have been plucked out from the sheet as it were. In reality the muscular sheet which lifts the 7th rib is not a single big engine but a string of engines, but as far as the pull on the 7th rib is concerned the result is the same whether there is one long or many short engines. Then in fig. 31 part of another muscular sheet is seen ascending to the 7th rib ; the fixed basis from which it acts is the pelvis ;

when the ascending sheet, which is also interrupted, contracts the front end of the rib is drawn downwards. Thus the 7th rib is worked by two complex engines: one raises it and the other lowers it; but it is plain, from *what has already been said about muscular engines, that* the one cannot act without the other. As the upper muscle shortens and raises the 7th rib, its opponent has to yield to a corresponding degree and yet keep a grip of the lever all the time. This harmony between the opposing muscles is established by the elaborate nerve mechanism already described (p. 43). At no part of a breath do the elevators and depressors loosen hold of a rib; all the time the opponent muscular engines are kept balanced and maintain a steady grip or balance on the rib. We have thus a power to control the bellows, as in singing and speaking.

Having seen the manner in which the 7th rib is hinged and the muscular engines which set this costal lever in motion, we are now to look at the way it helps in drawing in and expelling the breath. It is quite clear as the rib is raised towards a horizontal position that its front end will not only rise, but will also pass forwards; so will its cartilage and the breast-bone, which is carried on the cartilage (fig. 31). The ribs above and below, moving at the same time, will produce a similar effect. The front wall of the chest is raised and pressed forwards on the ends of the costal levers, thus enlarging the respiratory bellows from back to front. At the same time there is also an enlargement of the thorax from side to side, one produced in a very simple manner, which can be best studied in the 7th rib. Its axis or fulcrum is obliquely fixed to the backbone, so that as the lever rises it also moves outward; as it sinks it moves inward. If the axis on which the 7th rib moves had been set at a right angle to the spine, it would have remained the same distance apart from its companion of the opposite side as they rose and fell. But as their axes slope downwards they diverge as they rise and approach as they descend. The outward and inward movements are most extensive

in the lower ribs, but they are present in all. Hence when the ribs are raised they not only elevate and push forwards the front wall of the chest, but they also throw the side walls outwards, in this way enlarging the thorax in a transverse direction.

Thus in every breath we take twelve pairs of bony levers are set in motion; they are raised by one set of engines arranged as a complicated sheet—the external intercostal sheet of musculature. That sheet has its fixed base in the backbone; it cannot act unless the muscles which fix and regulate the vertebræ are also in action. The twelve pairs of levers are lowered by another elaborate set of engines—the internal intercostal sheet, which obtains its chief basis from which to pull in the framework of the pelvis. The great muscular sheets which ascend in the belly-wall from the pelvis to the ribs not only take a part in lowering the ribs and compressing and emptying the thorax but have also, when we are standing up, to support the weight of the viscera which are contained in the abdomen. When we see how great is the number of structures set in motion with each breath we take—levers, muscular engines, joints, and nerve centres—we are astonished that so complex a mechanism can be carried on with so little effort on our part.

We have seen that in all pumps of human invention, whether driven by hand, steam, or electricity, the power or engine has to be built as a separate machine. Nature, having that matchless kind of motor-power at her disposal called muscle, is able to build into its wall the engines which drive the pump, as we have seen is the case in the heart. She has the same advantage when she has to build bellows; the engines which work the respiratory levers, and the levers themselves, actually form part of the wall of the thoracic bellows. At least they form the side and front walls; but there is another wall, a very important one, which we have not yet looked at. This is the floor or diaphragmatic wall. The floor, we are to find, is built to act as a piston—a piston of a very

remarkable kind. The human machine, then, is provided with bellows of a new variety—a pistoned bellows.

When studying the respiratory chamber and the mechanism of the internal-combustion engine, we found it convenient to lay the cylinder open. We can throw the respiratory chamber of the human machine open in a similar way. This has been done in fig. 32; the front

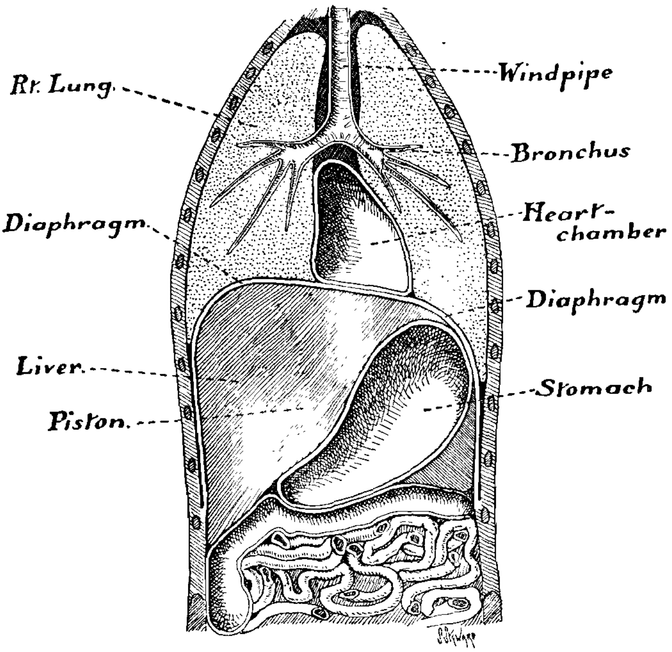


FIG. 32.—A vertical section of the human thorax exposed by removing the front wall.

wall has been removed, and the floor and side walls are seen in section. The shoulders quite mask the true shape of the thorax; when they are cut away we see that our chests are shaped like a cone, with its apex at the root of the neck and its broad base just above the waist. The upper part of the thoracic cone is filled by the two lungs, with the heart—the great pump—nestling between them, almost hidden by them (fig. 26). The lower part of the thoracic

cone is occupied by a piston which is as remarkable for its construction as for its effectiveness. The cone-shaped cylinder in which it works alters in dimension with every breath, yet the fit of the piston within the cylinder is perfect in every phase. It is a packed piston, packed with viscera — with great workshops which we shall examine later—the liver, the stomach, spleen, and other soft structures, all of them kept tense and turgid by the blood pumped into them by the cardiac pump. Indeed the diaphragmatic piston is packed by the top of the elastic column of viscera which fills the abdominal cavity. When we stand up the great muscular walls of the abdomen keep the top of the visceral column pressed within the diaphragmatic piston ; and when we lie down the viscera, by their own weight, keep it distended.

How is the visceral piston set in motion ? Nature builds her pistons as she builds her pumps and bellows ; the engine which moves the piston forms part of it. The piston has a muscular hood or covering called the diaphragm. The strongest part of this muscular hood is fixed to the backbone, just below the part to which the ribs are attached ; from this spinal basis the muscular fibres ascend over the back of the piston, ending on the fibrous caps or domes of the diaphragmatic piston. This constitutes the spinal part of the diaphragm. Then the muscle which covers the sides and front of the visceral piston obtains a fixed basis from which to act on the margins of the thorax—from the costal levers and costal cartilages forming the right and left margins. These fibres make up the costal part of the muscular diaphragm. The costal fibres are awkwardly situated in this sense : at one end they are attached to movable levers—the ribs ; at the other end they are attached to a movable piston. If the piston is fixed by being pressed up by the abdominal muscles, then the costal fibres will help to elevate the ribs ; if the ribs are fixed and the piston is movable, then they bring the piston down ; in either case they help to enlarge the thorax and draw in the breath. In quiet breathing the costal fibres, in the

majority of people, act both on piston and ribs, but the stronger spinal fibres have only one action : they cause the piston to descend. The result of combined action by the spinal and costal muscular fibres is to push the piston forwards as well as downwards ; hence we notice that at the pit of the stomach, just below the breast-bone, there is a forward swelling with each breath we take.

The muscular fibres of the diaphragm cause the piston in the floor of the thorax to descend, and thus enlarge the respiratory bellows on its vertical diameter from floor to apex of the thoracic cone. But how is this heavy piston returned after it has descended ? Which are the muscular engines which must yield as the piston is set in motion, and which will return the piston to start a new inspiratory cycle ? The opponents of the diaphragm are the strong muscular sheets which make up the walls of the abdomen —especially the upper parts of these sheets ; it is they which return the diaphragmatic piston. Thus are the abdominal viscera used to pack a piston—a piston which the diaphragm and muscles of the belly-wall use as a shuttle-cock with each breath we take and give.

This, then, is the story of how Nature has constructed the moving walls of the respiratory bellows, which she has fitted to the human machine. She has used the back-bone as the upright or standard for a support ; the side and front wall she has built out of levers and engines, so that when one set of engines are set in motion the side and front walls move outwards as well as upwards ; at the same time a piston packed with viscera and coated with muscular engines moves downwards and forwards. In this manner are the bellows enlarged in every direction, and air is thus drawn into the lungs. Then by setting another elaborate group of engines at work the movements of the levers and piston are reversed, and the air is gently expelled from the respiratory chambers. Man has not yet conceived a design which can rival or approach the respiratory bellows.

CHAPTER XIV

RESPIRATORY CHAMBERS

We have seen that the respiratory chamber of the engine of a motor cycle is a very simple matter ; it is merely the space within the cylinder. Connected with this space are two trapped or valved passages ; by one the current of petrolised air enters, by the other the burnt gasses pass out. It is clear, however, that a personal explanation is at this point necessary, for the cavity of the cylinder, now spoken of as the respiratory chamber, has been already described as serving two other purposes. It was compared to the main chamber of the heart—the great pump which maintains the circulation : it was also mentioned as the essential or driving part of an engine, and for that reason was regarded as serving the same purpose as a muscle cylinder. Further, we have seen that a space within the cylinder is also used as a combustion chamber. So many operations are mixed up together within the cylinder of an internal-combustion engine that some explanation is now necessary. The whole matter becomes cleared up if we think about what has happened to the homes in which our forefathers lived. Many of us have ancestors who lived, as a few crofters still do in the Highlands of Scotland and in the West of Ireland, in houses with only one room, where all the members of the family lived and slept, and where the fowls, pigs, sheep, and cows were also sheltered. The room served as byre, fowl-house, sheep-fold, kitchen, pantry, washhouse, bedroom, parlour, study, shoemaker's shop, carpenter's shop, and smithy. Then as the family became better off—

separate houses or chambers were set up one by one in which the various operations of life were conducted—until such an arrangement of buildings came into being as is now to be seen in a modern palatial farmhouse, where we find the operations which went on in the one-roomed hovel are going forward in a hundred separate buildings or rooms. The cylinder of an internal-combustion engine is a one-roomed hovel; all the work of muscles, pumps, and bellows is carried on in this one chamber, whereas in the human machine we enter that palatial state where separate establishments have been set up for the conduct of each kind of operation. Such is the case in the human body. If we want to understand the complexities of modern civilization we find the clues when we trace them back to their origin in one-roomed hovels. So too in machines; we find keys to unlock the complex ones when we search for them in the primitive machines of simple construction. That is the reason for our keeping a steady eye on the motor cycle as we try to understand the mysteries of the human body.

Having made this explanation, we shall now proceed to examine the respiratory chambers of the human machine. We cannot miss them if we follow downwards the passage-way taken by the breath. In fig. 33 a dissection has been performed to expose the main throughway for the breath in the nose, throat, and neck. When we take a breath, the air, after passing the relatively narrow doorways formed by the nostrils, finds itself in a warming-chamber—the right and left cavities of the nose, between which a partition has been set up. Internal-combustion engines work better when they are supplied with warm air; hence they run better in summer than in winter. The warming-chamber of the human machine has its side walls thrown into scroll-like radiators, which are kept hot and moist by the rich tide of blood which is being continually pumped through them by the heart. The air is not only warmed, but is also moistened and filtered in the chambers of the nose. The colder the air breathed, the greater is the tide of blood pumped through the radiators; the

drier the air, the more the moisture added to it. In the upper storey of the chamber, too, is set a very marvellous nerve mechanism—one which samples the air as it enters, and quickly discovers if there is in it anything which may

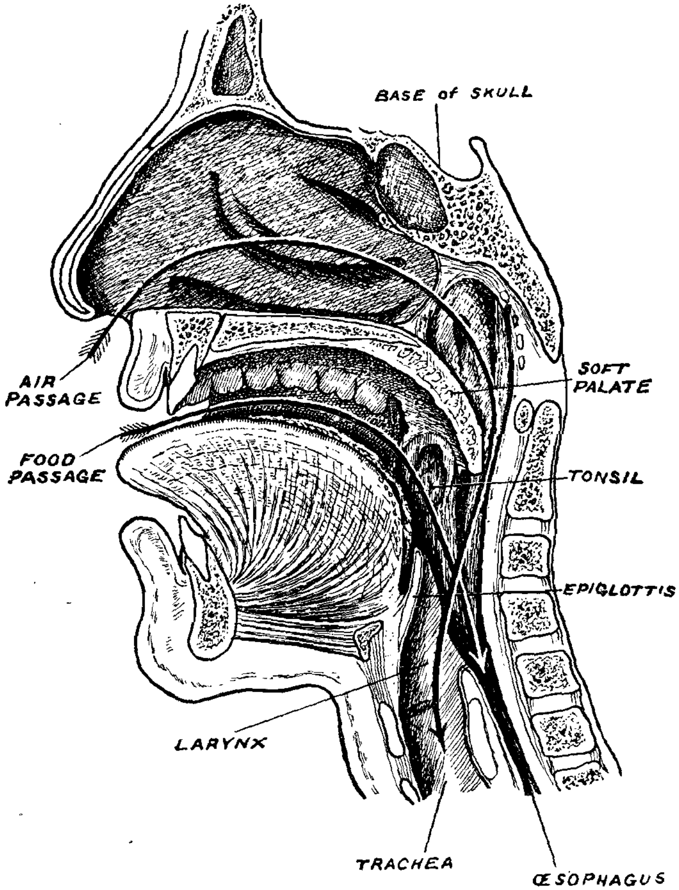


FIG. 33.—The air passages in the nose, throat, and mouth exposed.

prove injurious to the delicate lining of the respiratory chambers. Having been partly warmed as it rushes through the nasal cavities, the breath then enters the throat or pharynx—a wide open channel into which the cavity of the mouth also opens (fig. 33) ; hence when

the nose becomes obstructed we can breathe through the mouth, but then our mouths become dry and the air is not properly filtered or warmed. Passing down the throat the inrushing tide of air reaches, just behind and below the root of the tongue, the most delicately contrived doorway in all the body—a doorway leading into the larynx, trachea or windpipe, and lung passages or bronchi. When we swallow, the respiratory gateway closes the instant that anything solid or liquid enters the throat or pharynx (fig. 37). But when the tide of air enters it opens all the wider to let it rush towards the lungs.

There is a second gateway immediately under the first, known as the glottis, situated within the larynx, a structure which we can readily feel in our necks at the upper end of the windpipe. The glottis, through which the breath has to pass, is a triangular doorway with a sliding curtain at each side. These curtains can swing inwards until only a chink is left, or can be closed tightly so that the glottis or doorway is quite shut. These two swinging curtains are the vocal cords—the warning horn of the human machine (fig. 37, p. 176). Nature, following her usual habits of economy, has set it right in the breathing highway, so that she may use the respiratory bellows to sound a warning, utter a signal of distress, or give out those brain-signals which we call speech. The curtains of the glottal doorway are manipulated by a battery of very small muscular engines. As the inrushing breath approaches they pull the two curtains widely apart ; but if it should happen that the air contains an irritating vapour, then they keep them tightly shut, and we have the feeling of being suffocated.

Having passed the gateway formed by the vocal cords, the ingoing tide of air descends in the neck through the windpipe, which, when it has passed some way within the thoracic cage, divides into two branches or bronchi, one for each lung. We shall follow the current which enters the right lung. If you would obtain a true conception of the passages along which the current of air rushes until the final respiratory chambers of the right lung are

reached, then you must picture a miniature oak in full summer leaf, with trunk and branches hollowed out so as to form tubes right to the finest terminals which support the leaves. The trunk stands for the bronchus, the great branches for its main divisions, the smaller branches for the secondary divisions, and the terminal twigs which support the leaves for those fine air-pipes known as bronchioles. They lead to the respiratory chambers—represented by the leaves—where the real work of the lungs is carried on. All of these passages—except the terminal bronchial pipes—have hoops or rings of cartilage set in their walls to keep them open—much as soft rubber pipes may be kept open by having a spiral wire wound within them. All the air-pipes can be widened or narrowed, for on their walls are set muscle fibres of the involuntary kind. They relax or contract automatically according to the needs of the animal machine, and thus the pipes are widened or narrowed. It is, however, in the terminal bronchioles, leading into the respiratory chambers, that the muscular fibres become really important. If one of these terminal pipelets were to gape while all its neighbours remained small, then the respiratory chamber connected with the wide mouth would receive an unfair share of the incoming tide of air. Hence we find that the terminal twigs of the respiratory tree have not only flaccid walls, unstrengthened by cartilage, but are surrounded by cuffs of muscular fibres, just as we saw was the case with terminal arteries before they open into the capillary fields. The bronchioles of the lung are provided with a most delicate stopcock mechanism to secure an even distribution of the respiratory tide. That mechanism is regulated from nerve centres placed in the medulla. There is no need for securing an even distribution of the respiratory tide which enters the cylinder of the engine of a motor cycle. That is because there is only one chamber or cylinder ; if there were millions of chambers, as in the human lung, then a mechanism for just distribution of the air would be necessary.

We have only to see a ray of sunshine break through the air of the room in which we sit and live to realise how crowded our breath must be with fine particles of dust and soot. The nose filters off many of these particles, but multitudes are carried into the main passages, and not a few reach even the final respiratory chambers. It is very manifest that the air passages will become clogged—even become choked—just as certainly as a chimney will become filled with soot unless there is some arrangement for keeping it repeatedly swept. Chimneys lined with automatic sweeps have not yet been thought of, but a contrivance of this kind has been adopted by Nature for keeping clear and clean the air-ways to the respiratory chambers. Conceive a chimney set with boot brushes, so that their hairs or bristles form a continuous lining on which the soot from the smoke is constantly falling, and conceive, too, that the bristles are in constant movement, waving every particle of soot which falls on them in one direction—namely, from fire-place to the vent,—then you have some idea of the contrivance which Nature has adopted to keep the breath passages clear. The bristles or cilia which line the air passages are so delicate and small that they require a strong microscope to bring them within the range of our vision ; the backs in which the ciliary brushes are set and which keep the bristles in motion are microscopic brick-like corpuscles with which the air passages are paved. Cilia cannot work unless they are kept moist ; hence everywhere along the walls of the respiratory passages we meet with the mouths of small glands or workshops at which a clear sticky substance called mucus is being constantly thrown out to meet the needs of the cilia.

The layer of ciliated lining ceases suddenly as the respiratory chambers are approached and entered. The chambers have a thin delicate lining composed of living units which we may name pavement corpuscles. Stray microscopic particles of dust or soot may occasionally reach the respiratory chambers, sometimes carrying disease

germs with them. For their removal Nature calls in wandering microscopic scavengers known to medical men as phagocytes; they are noted for their hearty indiscriminate appetites. More frequently the disease-causing germs light on the main passageways and give rise to colds—afflictions from which internal-combustion engines are happily free. When a severe cold sets in, the ciliated corpuscles which line the trachea and bronchi become damaged by the invasion of germs; the mucous glands flood the passages; in a tussle with the germs, millions of scavengers fall victims, so that the air passages become clogged with a great accumulation of matter. In such states the respiratory bellows have to be called in to keep the air-ways clear; they are thrown into fits of convulsive action; this is a round-about way of saying that when we have a bad cold, we have to cough a great deal.

So far, we have been speaking only of the passageways leading to the essential elements of the lungs—the respiratory chambers. We must now look closely at a small set of chambers. In fig. 34 a minute piece of lung, such as could be covered by the eye of a darning needle, has been taken out and magnified. A little terminal pipe or bronchiole is seen leading to a set or cluster of air chambers or sacs. The bronchiole is just large enough to allow the finest sewing-needle to pass along it. Each chamber or sac is rather irregular in shape; its walls are exceedingly thin and delicate, but highly elastic, so that when blown up, and the air is again allowed to escape, it returns to its original size and shape. These are the sacs which are dilated when we take a breath; it is into these microscopic chambers that the air then rushes. One can hear it enter if the ear is closely applied to the wall of the chest in the act of inspiration. The noise is no more than a gentle rustle if the lungs are healthy. The air sacs are very small, only about $\frac{1}{10}$th of an inch in length and $\frac{1}{30}$th in width. In our two lungs there are about six millions of them, and therefore the charge of air which each holds is a very minute one. When we have taken the

biggest breath we are capable of, the lungs can hold a little under five litres of air—about one gallon. Of that amount 140 c.c.—about $\frac{1}{7}$th of a litre, or a quarter of a pint—is contained in the air passages, the rest is distributed among the millions of air sacs. The walls of the air sacs are not uniform in outline, but show saucer-like elevations on their outer surfaces, corresponding to recesses or depressions within. These recesses

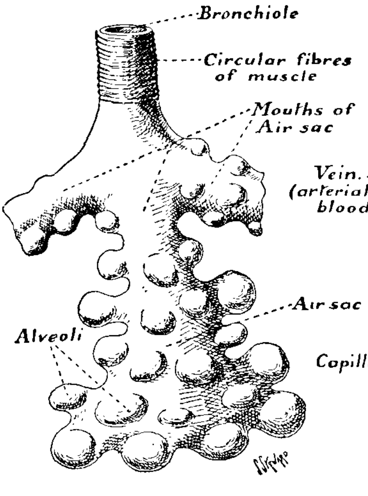


FIG. 34.

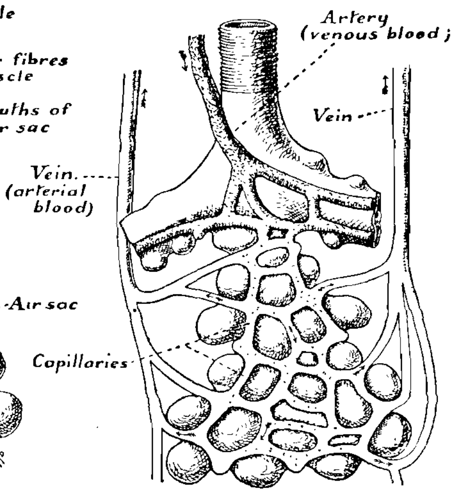


FIG. 35.

FIG. 34.—A cluster of air or respiratory chambers, with a bronchiole leading to it.

FIG. 35.—A cluster of air chambers with blood-vessels applied to them.

of the air sacs are known as alveoli or air cells, and they help to make the inner surfaces of the air sacs more extensive. The interior of an air sac, thus increased by the presence of the alveoli, is lined by a delicate, thin, transparent membrane. If the lining membranes could be stripped off from all the sacs of both lungs and spread out as a continuous sheet, it has been calculated that it would cover the floor of a room which measures 30 feet square. The membrane which lines the lungs of a man of middle size is supposed to

be about thirty times the area of the skin which covers his body. This membrane, if inflated, would form a balloon 10 feet in diameter, the cover being little thicker than the film of a soap bubble. The greater part of every breath we take is distributed over the entire surface of this extensive membrane.

We cannot empty the air sacs of our lungs completely, however hard we may squeeze or compress our chests. Nature has taken care to render that impossible—for a reason we are now to explain. It is not so with the engine of a motor cycle; it clears all the air from the cylinder with each exhaust stroke. The minute air sacs of the two lungs of a grown man, as we have seen, can hold rather less than 5 litres (4700 c.c.) of air when the deepest breath is taken, but in ordinary breathing they contain only about 3 litres. With each expiration about half a litre (500 c.c.) is expelled from the two lungs[1]; from each air sac only one-fifth is discharged with each breath; with the next inspiration a fifth is again added, but in all phases of the respiratory tide the air sacs retain at least four-fifths of their charge. If we breathe out very hard we can reduce the amount in the air sacs to one-third of the normal charge, but the remaining or residual amount cannot be expelled by the greatest effort we can make.[1] The mouths of the respiratory chambers are so framed that they close automatically or collapse when their charge of air is reduced to one-third of the normal.

To understand why the air sacs should be thus controlled and safeguarded we must look at the nature of the operations carried on in them. At one time it was supposed that their cavities were combustion chambers like the cylinders of engines, and that the heat which warmed the body was really produced in the lungs. Presently it will be shown how chemists discovered that combustion is carried out elsewhere in the body. The air sacs are, however, connected with combustion. We have now to see how the red blood discs are brought to them in order that they may pick up the loads of oxygen which they carry off to feed the myriads of vital com-

[1] See Appendix G, p. 297.

bustion chambers throughout the body. Also we have to see how carbon dioxide, a product of oxidation or combustion, is brought back from the tissues of the body and is discharged into the minute respiratory chambers of the lungs.

The mechanism is very simple. In fig. 35 the walls of a cluster of air sacs are shown, covered by a close-meshed network of capillary vessels. Into the meshwork opens a terminal artery ; issuing from it is a commencing vein or venule. The artery is a twig from the great vessel which springs from the right ventricle of the heart—the pulmonary artery ; the venule ultimately joins one of the veins which discharges its blood into the left auricle of the heart. Every one of the air sacs, which we have roughly estimated as numbering six millions, is surrounded by a capillary field ; the fields are fed by arterioles and drained by venules. The right ventricle is the pump which keeps this extensive capillary field constantly flooded with venous blood. Every pumpful of arterial blood which is thrown into the aorta by the left ventricle is accompanied by an equally great discharge of venous blood, thrown into the pulmonary artery by the right ventricle. Files of red blood-discs are constantly being hurried through the capillary fields in the walls of the air sacs. They have been robbed of their oxygen while passing through the tissues of the body. The red substance of the discs has a remarkable affinity for oxygen, and when the capillary fields of the lung are reached the discs quickly renew their loads and are then sped onwards in the veins leading to the left chambers of the heart. The blood also brings back from the tissues charges of carbon dioxide carried in its plasma and corpuscles. The carbon dioxide diffuses into the air chambers as the blood circulates through the capillary fields. Between the blood circulating in the capillaries and the air in the respiratory chamber there is but a thin delicate partition which is always moist and through which gases in solution can diffuse very readily.

We now ask the question—Why should not the respiratory chambers be completely emptied of air ? The

answer to that question has been given by Dr J. S. Haldane of Oxford University. He discovered that the respiratory chambers or sacs of the lungs are laden with air which is always charged with the same proportion of CO_2—namely, 5·5 volumes of CO_2 to every 100 volumes of air. He observed that if the proportion of CO_2 becomes higher, then the breathing is quickened, thus washing out more CO_2 from the respiratory chambers and replacing it with air. If the proportion becomes less than normal, then the breathing is slowed until the usual proportion is restored. It is now quite well known why the rate of breathing alters as the proportion of carbon dioxide in the air sacs is altered. In health, arterial blood is slightly alkaline in reaction ; if it contains a charge of CO_2 it becomes acid in reaction,[1] and if such blood is supplied to the medullary nerve-centres which control the muscles of respiration, then these centres are excited and send out messages which set the muscles of respiration to work more vigorously until the blood regains its normal quality. Not only are the respiratory nerve centres disturbed by an excess of CO_2 in the blood supplied to them ; they are also thrown into an equally excitable state if there should be a deficiency of oxygen. The rate of our breathing is automatically controlled by the percentage of oxygen and carbon dioxide in the arterial blood —the two substances connected with combustion. The amount of these substances in the blood depends on their proportion in the air filling the respiratory chambers of the lungs. The more we work, the greater is the combustion in our bodies. The greater the combustion, the more rapidly must we renew the air in the respiratory chambers by breathing. In this manner a very simple and yet very effective mechanism has been invented by Nature to keep the respiratory bellows working at a rate which exactly meets the needs of the human machine.[2] We can now see why Nature has arranged the mouths of the respiratory chambers so that they become automatically closed at a certain stage of emptying. At least one-third of the charge of air is retained. The automatic

[1] See Appendix G, p. 297. [2] See Appendix B, p. 276.

regulating mechanism would be destroyed if the chambers were quite emptied. Nay, if emptied their walls would collapse, and the flow of blood through the capillary fields of the lungs would thus be blocked. Death would soon follow from a complete stoppage of the pulmonary circulation.

Before bringing this chapter to an end, there is one very important matter to which I must allude—one which has to do with maintaining the lungs in a healthy condition. Like all wise engineers, Nature designs every one of her fabrics so as to fulfil the law known as the "factor of safety." When an engineer builds a boiler or designs a crane, he builds and designs so that the boiler will withstand a pressure of steam and the crane will support a load ten times the amount required in the course of ordinary use. Nature builds her engines, levers, pumps, and also her bellows, on this principle. In ordinary sedentary occupations men and women do not use the respiratory chambers of their lungs to one-tenth of their full capacity. If lungs are always used, day after day, at this low rate, they are more likely to suffer damage than any other part of the human machine. They are so constructed that we may use only one part of them fully, the rest being employed to merely a minimum degree. Numerous sets of respiratory chambers, under such conditions, may be regarded as temporarily shut down. Unfortunately, we have always been taught, have always supposed, that a lung expands equally in all its parts when we take a breath, much as if it were a simple bellows. Every movement of an ordinary bellows, however slight, diffuses the indrawn air throughout its entire chamber. The lungs, as we have seen, are set with millions of miniature air sacs ; the pipes or bronchi which conduct air to them are stout ; they radiate out into the lungs like the branches from the trunk of a tree, or, if I may alter the simile, like the rays of a lady's fan. Between these fan-like bronchial rays are set myriads of air chambers. When we take a full breath the thoracic bellows expand in such a way that all the rays

of the pulmonary fan separate, and as they separate the air chambers in their forks expand and air rushes into them. But this only happens if all three walls of the thoracic bellows are set in motion—its front and side walls and its floor or diaphragmatic piston. If we breathe lazily we may move only one part of the chest wall, and then it is only one part of the pulmonary fan that is fully expanded. Hence the importance of setting the human machine in full motion for some minutes each day. If we set the machine thus going combustion takes place in the body; the nerve centres which control the movements of the respiratory bellows are at once flooded with impure blood and automatically stimulated. They are stimulated so that more oxygen may be taken in and more carbon dioxide discharged. A child needs no teaching how to breathe; set it running, playing, climbing trees or stairs, and it cannot help using its lungs fully and rightly. There is no more need to teach a child how to breathe than how to suck—Nature has seen to that. But every child has to be taught, and we have all to learn, that under modern conditions of life there are temptations to abuse Nature's contrivances by neglecting them, by failing to set them fully and frequently in motion.

CHAPTER XV

CONTRIVANCES FOR REGULATING THE HEAT OF THE HUMAN MACHINE

ON a cold winter's day you have seen a man, with his body somewhat bent, his head drawn down on his shoulders, rub his hands, stamp his feet, and beat his arms. He tells you he is shivering with cold, but when you measure the temperature of his body by placing a *thermometer* in his mouth you find it is almost the same as your own—at little over 98° Fahrenheit (37° Centigrade). Then you meet the same man on a very hot summer's day ; the iron railings which in winter were so cold that they stung when touched are now too hot to hold comfortably ; the man is carrying a heavy burden and sweat drops from his forehead. You again measure his temperature and find it is almost the same as on the coldest day of winter. The iron railings, the sunbaked pavement, the air, and all the man's surroundings have been raised to 100° in temperature, but the man's body is neither warmer nor colder than before. Engineers have not succeeded in making a moving machine which can maintain the same temperature in all climates and in all weathers. We have seen something of the contrivances which they apply to keep engines cool—the circulation and evaporation of water, currents of cooling air, even the application of clothing, but all of them are mere makeshifts. We are now to inquire into the contrivances which Nature has applied to regulate the temperature of our bodies.

Our inquiry follows naturally on the two preceding

chapters which deal with the thoracic bellows and the respiratory chambers of the lungs. From olden times, long before Harvey's day, men noticed that the lungs surrounded the heart so as to clothe it—the great combustion chamber, so they thought, from which heat and life were distributed to the rest of the body. They knew that the heat of the body always remained about the same, and must therefore be regulated. It was natural for them to believe, when they saw that air entered the lungs and was thus brought in contact with the heart, that breathing and the lungs were Nature's contrivance for *regulating* the temperature of the body by cooling the heart—the main combustion chamber. We shall see that modern physiologists estimate that only a little over one per cent. of the total heat produced in the body is carried away by the breath. Nevertheless, even up to the time of his death in 1657, Harvey looked upon the lungs as a means of cooling the heart.

Twenty years spent in dissecting and thinking made Harvey master of the heart's secrets. It took two hundred years of labour by a succession of men to discover the use of the lungs. Their use was eventually discovered not by medical men, but by chemists and natural philosophers. We shall learn many secrets connected with the heat regulation of the body if, for a short space, we follow in the footsteps of the men who, one after the other, succeeded in making discoveries which brought the true use of the lungs into the full light of day. In 1660, when the line of Stuart kings was restored to Britain, and three years after Harvey's death, the Hon. Robert Boyle performed an experiment of a new kind. He placed a lighted candle under an inverted bell-jar, and drawing the air off by means of a newly invented contrivance, the air-pump, showed that the candle went out when the air was exhausted. He replaced the candle by a live mouse; when the air was extracted the mouse died. Air was thus decisively shown to be necessary to sustain both combustion and life. There was, therefore, a resemblance between combustion and

life. Almost at the same time Malpighi, an Italian anatomist, was examining the lung of a live frog; he then discovered capillaries—the channels which connect arteries to veins. He saw, too, that respiratory chambers are surrounded by capillary fields of blood. Then the next important discovery, which happened some five years later, was made by Dr Richard Lower, a native of Cornwall. It was a simple observation made on live animals, namely, that blood changed from a dark lake to a bright crimson colour as it passed through the lungs. The meaning of that change he could not know. Three years later, in 1668—you observe discoveries are following fast on each other,—Dr John Mayow, also of Cornish descent, when about to complete his studies at Oxford University, made experiments somewhat like those Boyle had carried out. He placed a mouse under one bell-jar and a lighted candle under another, but did not exhaust the air as Boyle had done. The mouse died, the candle went out, and he observed that they were not choked or extinguished by fumes, but died because they had exhausted some essential part of the air; of course we know now what that exhausted element was.

For many years no one saw that these discoveries threw any light on the uses of the lungs; hence men went on believing that they were for cooling the heart. And so we pass over nearly a whole century, until 1754, when Joseph Black, a young graduate of Glasgow University, had to prepare a thesis in order to obtain the degree of Doctor of Medicine. He made four discoveries in quick succession: (1) That when limestone was burned a gas was given off which he called "fixed air," but which modern chemists name carbon dioxide (CO_2); (2) he found out that he could always recognise this gas by passing it through a solution of quicklime, the solution becoming white and chalk being precipitated in it; (3) that when air in which a candle had been burned was passed through lime-water it gave the same characteristic reaction; therefore during combustion fixed air was produced; (4) air which had been breathed, like air in which

a candle had been burned, also contained fixed air. But neither Dr Joseph Black nor any of his fellow-workers saw that these discoveries threw light on the use of the lungs.

In 1771, when Dr Joseph Black had become Professor of Chemistry in the University of Edinburgh, Mr Joseph Priestley, a native of Leeds, where he was born in 1733, a clergyman of the Unitarian Church by profession and a natural philosopher by instinct, commenced a series of experiments which led him up almost to the discovery of the real use of the lungs. He filled in his idle moments by inquiring into the nature of the air which men breathed in living rooms. He found that air which had been breathed for some time by a mouse under a bell-jar, so that it might no longer support life, could be restored by growing plants within it. He discovered, too, in the course of other inquiries that the gas given off when red oxide of mercury was heated caused a lighted candle, when placed in it, to burn much more brightly ; a mouse could breathe this new gas and live vigorously. He made a bad guess as to its nature and called it "dephlogisticated air"—the element to which Lavoisier, the great French chemist, afterwards gave the name oxygen. Almost at the same time (1774) oxygen was discovered in Sweden by Scheele. Very soon afterwards the Hon. Henry Cavendish, a rich landed gentleman who devoted his life to experimental researches, found out that, when Priestley's dephlogisticated air (oxygen) was burned with certain proportions of "inflammable air" (hydrogen), both gases disappeared and water was formed in their place. He was the first to realise that water was formed during combustion and was made up by the union of definite proportions of two elements—hydrogen and oxygen.

Thus in England, by 1783, all the facts had been discovered relating to the similarity of the gases formed during the burning of a candle and the breathing of an animal ; but none of the British investigators had succeeded in putting the facts together, so as to show that

the chemical processes which take place during respiration and combustion are identical. This was done by the cleverest chemist and natural philosopher then in Europe —Antoine Laurent Lavoisier. He was ten years younger than Priestley and twelve younger than Cavendish, and whilst they were circulating round the circumference of the problem of respiration in England he went straight to its centre in France. He proved that the same chemical changes took place in the lungs as in a lighted candle. "Fixed air," given off by both candle and lungs, he showed to be produced by the union of definite proportions of carbon and oxygen; water, which was also formed, he proved to result from the union of hydrogen and oxygen. Combustion and respiration were, therefore, processes of the same kind, processes in which hydrogen and carbon united with oxygen. The lungs, in Lavoisier's opinion, were furnaces by which the body was, not cooled, but heated; breathing was a means of bringing fresh oxygen to the combustion chambers of the lungs.

The conception which Lavoisier formed as to the use of the lungs may be represented by a simple experiment. In fig. 36 a rubber membrane has been tied over the mouth of a large inverted glass funnel, so as to form a movable diaphragm. On the upper surface of the rubber diaphragm stands a lighted candle. Presently the candle, exhausting the supply of oxygen within the funnel, begins to go out. But if the diaphragm be gently worked, so as to bring breaths of fresh air down the pipe of the funnel and throw out breaths of burned gases, then the flame revives, and may be kept alight until the candle has burned down in its socket. Lavoisier conceived that in the myriads of minute air sacs of the lungs a form of combustion was going on not unlike that represented in the inverted glass funnel.

It took nearly fifty years more to make quite certain that combustion chambers are not confined to the lungs, but, as we have already seen, exist in every particle of the living body. Every microscopic unit, every corpuscle of the tissues, is really a furnace in which a peculiar kind

of flame is being constantly fed. We have seen how the combustion chambers of the muscular engines are stoked. We must refer again to these ultra-microscopic combustion chambers in the cylinders of the engines of the human body (see fig. 6, p. 37), for when we recall the fact that muscles make up more than one-third of our total weight it becomes evident that the combustion which goes on in them has much to do with maintaining the warmth of our

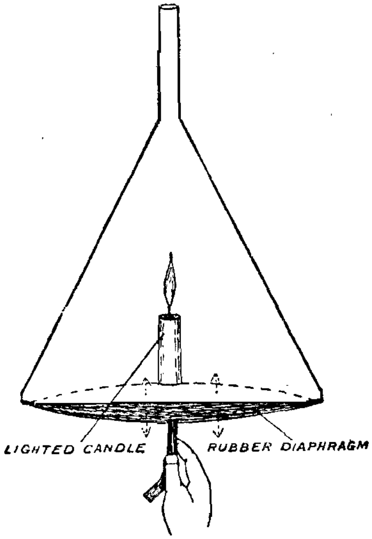


FIG. 36.—An inverted glass funnel, in which a lighted candle has been placed, set upon a movable diaphragm.

bodies. When we examine the living muscle cylinders we see long processions of red blood-discs arriving in the capillary tubes surrounding them. The red corpuscles are packed with loads of oxygen, picked up in the walls of the respiratory chambers of the lungs. We see these red discs unburdened of their loads as they file through the capillary fields which surround the muscle cylinders, the oxygen being drawn into their combustion spaces. At the same time there arrive, carried in the fluid part of the blood, substances which serve the muscle cyclinders as fuel. We know very well that the fuel and the oxygen

have to be compounded and stored as a living mixture before they can be used by the cylinders and thus turned into work and heat. We know that this mixture is consumed or burned; when muscular cylinders are working hard it is consumed at ten times or even twelve times the rate it is used up when the engines are at rest. Clearly one way of warming the body is to set the muscles at work; that quickens combustion—as every one of us already knows. We have seen, too, how the chief product of combustion (CO_2) is carried away from muscles in the blood of the veins and ultimately discharged into the respiratory chambers of the lungs, being finally expelled from the body with the breath.

If muscles represent the most extensive system of furnaces in the body, they are by no means the ones which give out the fiercest heat. The liver, we shall find, is a vast chemical factory busy with processes in which a great deal of heat is produced. Indeed, all the organs concerned in the digestion of food are also producers of heat; so are the kidneys, and also the lungs. When we work our brains very hard we can feel that our heads become hot. Every one of the countless myriads of living units, fitted together so as to form a single human machine, is a microscopic slow-combustion stove.

We are now in a position to realise what a marvellous thing it is that the human body can maintain its countless fires burning at the exact rate which keeps the temperature of the whole machine just above 98° F. in all weathers and in all climates. We know how difficult it is to keep a room at a comfortable temperature. If it becomes too cold, we warm it by making the fire up or by shutting doors and windows. If a room becomes too warm, we let the fire burn low or open windows and doors to permit draughts of fresh air to flood and cool it. Nature adopts similar means to regulate the temperature of the body; she may maintain it at the same warmth by raising or lowering the rate of combustion, or by increasing or decreasing the rate at which the heat escapes from the

surface of the body. We shall see that she can alter and control both combustion chambers and skin surfaces.

A driver regulates the rate of combustion in his engine by turning the throttle valve on or off. The steeper the hill in front of him, the wider he opens the throttle and the greater becomes the consumption of petrol and of air. The engine becomes hot; it may become overheated and unworkable in spite of the means he adopts to keep it cool. He may bring the engine to a standstill by closing the throttle; combustion then ceases; the engine quickly cools to the temperature of the surrounding air. Except at death the countless throttles which control combustion in the human machine are never turned off; they are so regulated that when the body is at rest combustion still goes on at a certain rate, for we have seen that the human engines never stop; they have always their "steam up." The manner in which the throttles are set and controlled to maintain a regulation rate of combustion when the human machine is at rest is a mystery of life which has not been discovered, but we do know a little of the mechanisms by which the regulation speed may be altered so that the rate of combustion may be raised or lowered according to the needs of the body. The will can indirectly turn on the throttle valves of the combustion chamber when it sets the muscles to move the body and perform work. Dr Leonard Hill[1] found, when he kept his body at rest, that he gave off in his breath 301 c.c. of CO_2 per minute, but when he went swimming the rate of combustion was increased more than twelvefold; he then gave off 3804 c.c. of CO_2 per minute. We cannot move a muscle in our bodies without raising their temperature, however small the rise may be; at the end of a long race the heat of the runner's body may have risen from 98° to 105° F.; even Nature's mechanism for regulating temperature may fail when overtaxed. Still, how perfect it usually is

[1] *A Textbook of Physiology*, by Martin Flack and Leonard Hill. The reader is referred to this excellent work for original data connected with respiration and temperature

may be judged from another instance given by Flack and Hill. A soldier with a body-weight of 154 lb. and carrying a pack weighing 68 lb. was found to produce, every five minutes, sufficient heat to raise the temperature of his whole body 1° F. If he had been enclosed in a vacuum coat, so that heat could not escape from his body, his temperature at the end of an hour's march would have risen from 98° to 110°; in nine hours more it would have passed boiling-point. Yet men make marches for five hours at a stretch, and at the end of the journey their temperatures are found to be scarcely altered. Muscles, then, are a source of heat; by setting them in motion the amount of heat produced in the body is increased many times. Shivering, as Dr Hill has pointed out, is one of Nature's means for increasing heat production by setting muscles into involuntary action. We see, too, why a man who is cold beats his arms, rubs his hands, and stamps his feet to warm his body.

Nature has certain other mechanisms she uses for increasing the production of heat in the human body. The organs of digestion, such as the liver, when fully at work, particularly if nourished on a meat diet, are most important sources of heat, so active are the chemical processes which go on in them. The feeling of chill which may accompany a meal is not due to a lessened production of heat, but to the withdrawal of blood from the surface of the body to supply the needs of the organs of digestion. Fats, when freely consumed in the tissues of the body, serve as a particularly good heat-producing fuel. Then there are other means. We can make a fire burn faster or slower by adding certain substances to the fuel. Amongst various substances or drugs which the thyroid gland of the neck throws into the blood of the human body is one which can hasten the rate of combustion in its tissues, and thus increase heat production. Sometimes thyroid extract is taken by people with the object of burning up superfluous stores of fat which have accumulated in their bodies. There are probably other substances

which serve to regulate combustion in the body of which we have no knowledge as yet.

There remains to be mentioned a very important mechanism for controlling the heat of the body. All over the skin are placed minute transmitting stations—or temperature transmitters. Some are sensitive to those conditions we regard as cold, others are sensitive to conditions which give us the feeling of warmth. Messages are being continually taken up at these receiving stations concerning the state of the surrounding temperature and transmitted to central exchanges in the spinal cord and brain stem. From these central exchange stations other messages are dispatched to all parts of the body regulating and controlling the rate at which their combustion is carried on. A cold day sets messages on foot that speed up combustion ; the messages of a warm day damp down the sources of heat. The skin, then, is the end organ of a great heat-regulating mechanism. How we stand heat and cold depends on how perfectly this mechanism reacts. Man is the most naked of all living hot-blooded machines. There was a time, before he learned to clothe his body, when his comfort—his power to live—depended on the sensitiveness and effectiveness of this skin-regulating mechanism. It was a costly contrivance, because it consumed so much of the fuel of the body. In modern days we depend on it less because we have learned to make warm clothes and build houses in which a more equable temperature can be maintained.

So far we have been speaking of the mechanism for controlling heat-production in the body. We come now to an equally important matter—the contrivances which Nature has adopted to regulate the escape of heat so that the mass of the body will be maintained at a temperature between 98° and 99° F. Her chief contrivances to secure this end have been worked out in the skin. The human skin has been made into leather and used for binding books ; the tanner rubs off the friable surface layer or epidermis ; the deeper stratum or cutis, a tough fibrous-textured material, forms the leather. The skin of a man

of medium size, when removed and spread out, would make a square sheet measuring 5·5 feet along each side—about 30·2 square feet. In life these 17 feet of cutis form a vascular sheet, a great capillary field, flooded with a rich supply of blood. The arterioles supplying the field with blood are provided with the most sensitive of stopcock mechanisms. These mechanisms are controlled by centres set in the spinal cord and brain. The controlling centres are supplied with messages from the temperature transmitters which, as we have seen, are set everywhere in the skin. On a warm day the stopcocks are opened, the skin is flooded with blood ; heat radiates from the surface of the body ; currents of air rise from the suffused skin and rob the body of its heat. On a cold winter day the opposite happens ; the stopcocks are turned off ; the skin becomes pale and bloodless ; the radiation of heat is diminished. Physiologists estimate that about three-fourths of the heat produced in the body escapes by way of the skin.

What happens if we are placed in surroundings which are warmer than the normal temperature of the body ? A man may live in a chamber which is kept hot enough to cook a fowl and yet his temperature may rise only a degree or two above the normal. If his body were not a living thing it would absorb heat and become cooked. Nature has used the simple contrivance of evaporation to keep the body cool. A drop of sweat evaporated on the skin takes away from the body as much heat as would be sufficient to raise two other drops above the boiling-point of water. Sweating robs the body of heat and thus cools it. Hence the surface of the skin is studded with the openings of sweat glands ; in most areas of the body there are about 500 sweat glands to a square inch of skin ; in the sole of the foot and palm of the hand they are four or five times more numerous. The sweat glands, like the blood-vessels of the skin, are controlled from nerve mechanism in the spinal cord and brain stem. If the blood supplying these control centres becomes warmer than the normal body temperature, their nerve cells are stimulated and

nerve messages are sent out which set the sweat glands in action. The hotter and drier the air, the quicker does evaporation take place and the more rapidly is the body cooled; when the blood returns to the normal warmth of the body then it ceases to stimulate the controlling nerve centres, and the messages which keep the sweat-glands in action cease to be dispatched. The loss of body fluids, through sweating, gives rise to a feeling of thirst; a fireman in the stoke-hole of a steamer will consume 12 pints of fluid in a shift, most of which is evaporated as sweat, and thus the temperature of his body is kept at a normal degree of warmth. If, however, a hot atmosphere—one above 98°—is laden with moisture two things happen: (1) sweat cannot evaporate and thus cool the body; (2) the body absorbs heat much more rapidly in a hot vapour-laden atmosphere because a moist air is a much better heat conductor than a dry one. Very soon a point is reached when the heat-regulating mechanism of the body breaks down and then "heat-stroke" occurs. The tissues of the brain cease to work when the temperature mounts to 105°; if it passes above that degree life cannot be maintained for many hours, because the central nerve system undergoes destructive changes.

There are several other contrivances by means of which the heat of the body is economised. Fat is an excellent non-conductor of heat. We are provided with inner wrappings of this material, particularly one placed just under the skin. Whales, which have to maintain an even body-temperature in Arctic seas, have an enormous subcutaneous covering of fat or blubber. Blubber serves the Greenland whale as house and clothes. Even oil-forming glands—sebaceous glands—are set closely in the human skin to grease its surface, so that moisture may not soak into it and cool the body by evaporation. In spite of all provisions, however, moist, cold winds throw a great strain on our heat-regulating mechanisms. Dr Leonard Hill has shown how an atmosphere, laden with moisture, can steal heat stealthily from our bodies without ever awakening the temperature-regulating mechanism,

thus permitting our bodies to become overcooled. Heat can escape from the body much more easily on a damp day than on a dry one. Dr Hill has also drawn attention to the demands made on the heat-producing system by cold, biting, damp winds. Such a wind pierces our clothes and sweeps from their meshes the curtain of warm air maintained there by the body heat. No sooner is one curtain gone than the body starts to build up another layer of hot air, which is swept away in turn by the blast which follows. And so the heat supply of the body is steadily drained to keep up the surrounding curtain of warm air. Now it is just at such times that disease-producing germs may gain an advantage, unless our heat-producing and heat-regulating mechanisms are perfectly sound. Such a drain on our heat supply stimulates the vitality of the sound body, but it lowers the powers of resistance of the body which has been weakened, so that the heat-producing mechanism does not respond to vagaries in the weather. It is under such conditions that the micro-organisms which cause "colds"—everyone has them lurking somewhere in his breath passages—make a successful attempt to invade the living systems of the human machine.

CHAPTER XVI

A SURVEY OF THE WORKSHOPS AND LABORATORIES OF THE HUMAN BODY, WHERE FOOD IS TURNED INTO FUEL FOR THE TISSUES

In order that a machine may perform work, be it made of metal or of living flesh, it must be provided with a system of parts which will maintain a constant supply of the food, aliment, or fuel consumed in the combustion chambers of the machine. To an arrangement of parts of this kind human physiologists give the name of alimentary system. In the human machine we shall find that this system is made up of a series of workshops or laboratories linked together by a novel and cleverly contrived transport system, while in the motor cycle the parts are few and arranged in the simplest plan conceivable.

Before proceeding to compare the alimentary system of a motor cycle with that of the human body, it may be well to answer an objection which is likely to be raised by the reader at this point. He may question whether the word fuel—a substance which can be burned in an engine—may be applied rightly to the food or aliment which is consumed by human beings. The answer of the modern physiologist on this point is decisive. He has found that a pound of sugar, whether consumed in the combustion chamber of an engine or in the myriad recesses of the human body, gives off in each case exactly the same amount of heat. He estimates the value of a food just as an engineer estimates the value of a fuel by measuring the amount of heat it gives off when burned.[1] A human machine of medium size and doing strenuous manual

[1] See Appendix II, p. 308.

work needs a daily allowance of fuel which may be represented by 30 oz. (850 grammes) of sugar. Of that amount 26½ oz. are dissipated in heat—in keeping the machine warm and in maintaining it; only about 3½ oz. (a little less than 12 per cent.) is converted into effective mechanical work.[1] With an equal amount of petrol (30 oz.) a motor cycle will carry a man over nine miles of ordinary undulating country road; 25½ oz. of the fuel supplied is wasted as heat; only 4½ oz. (15 per cent.), or much less, is transformed into effective work. The human heart transforms 25 per cent. of the fuel with which it is supplied into effective work; the rest goes to heat the body. We are justified, therefore, in speaking of food as fuel. The fuel of an engine, however, needs no flavouring or seasoning; if the petrol has been distilled, if all grit or sediment has been filtered off before the cylinder is reached, then all has been done that is needed to satisfy the palate of an engine. It is otherwise with the fuel supplied to the human machine; certain ingredients in minute quantities have to be mixed with it to satisfy the palate and meet the needs of particular requirements of the human machine.

Nothing could be more simple than the alimentary system of a motor cycle. The fuel is poured through a mouth or opening into a stomach or tank (fig. 1 p. 10); from the tank the petrol is carried by means of a feed-pipe—the alimentary canal—to an apparatus—the carburettor (fig. 1)—which absorbs the petrol and transforms it into a combustion mixture. At the carburettor the alimentary canal ceases, for there the fuel actually enters the engine. The carburettor, we shall see, corresponds to an elaborate machinery which has been built into the containing wall of the alimentary system of the human body—a machinery which selects and absorbs from the food such elements as are to be used in the body as tissue fuel. Just before the petrol enters the carburettor it passes through a float chamber (fig. 1) which automatically regulates the rate of flow according to the amount of absorption. We shall see that there are corresponding mechanisms set along

[1] See Appendix J, p. 312.

ıe alimentary tract—stopcock or sphincter mechanisms 'hich regulate the rate of progress of the alimentary ɔntents. The bowel, then, of a motor cycle ends ɔruptly at the jet aperture of the carburettor; there ; no vent as in the human machine. That is because etrol is a perfect fuel; there is no need for a vent or ɛctum because there is no refuse to discharge.

The alimentary tract of a motor cycle is a simple ffair, very different from the bewildering arrangement of arts we meet with in the same system of the human ıachine. If mere simplicity be a merit, the motor cycle, ; far as an alimentary system is concerned, seems to old an advantage over the human machine. The :omach of a motor cycle is, however, a delicate thing; must be fed with fuel already digested—already in a ɔndition suitable to form the basis of a combustion ıixture. Petrol, the food of engines, if modern geologists 'e rightly informed, is the fuel which was stored up . the livers of extinct animals, vertebrate beasts which ved in marshes and seas, now buried beneath strata : solid rocks hundreds of feet in thickness. In the vers of living sharks and certain other fish we know ıat there is stored up a carbohydrate material, very milar to petrol, which is used by them as fuel to drive ıeir muscular engines in swimming. The petrol which .rries a cyclist so swiftly along we are justified in re- ırding as fuel which extinct monsters had stored up their livers many millions of years ago to carry them .rough old-world seas in search of prey.[1] The fuel of a otor cycle is already digested. It is otherwise with the ıman machine; it has to be provided with a plant or ıtfit which can convert the raw material provided in e natural products of the earth into a form of fuel ıitable for combustion in the tissues of the body. [ence the elaborate arrangement of its alimentary system.

Before actually setting out to examine the machinery the alimentary system, there are one or two matters ınnected with its general management which require ı be mentioned. If the petrol tank should run empty

[1] See Appendix J, p. 312.

then the engine comes to a standstill, perhaps in an awkward place such as a busy crossing. Hence a warning signal may be attached to the tank which is made to sound an alarm when the stock of petrol needs replenishing and keeps on attracting attention until the tank is again filled. The human machine has been fitted with a mechanism of this kind which we call hunger. We have seen how the need for breath or air-hunger is regulated by nerve centres in the medulla. When the blood is lacking in oxygen or becomes charged with more than its usual percentage of carbon dioxide the medullary nerve centres are excited and immediately take forcible control of the muscles of respiration. Apparently something of the same kind happens when the available supplies of fuel or of water run short in the human machine. The state of the blood—so we are led to suppose—sets certain nerve centres agog. In the case of hunger it is a centre which is connected with the stomach and has control of its movements. Prof. W. B. Cannon observed that the pangs of hunger were accompanied by vigorous waves of contraction which passed along the stomach. The signal for restoking in the human machine is not the ringing of a bell but the writhing of an empty stomach. The signal for thirst is connected with, and localised in, the throat. Hunger and thirst are imperious contrivances; they are the dictators of mankind; we spend the greater part of life in trying to satisfy them. In connection with the sexual system of the body there is also a set of contrivances of a similarly imperious kind, often challenging the will for command of the human machine.

In the mouth and throat, the first chambers or workshops connected with the preparation of fuel for the human machine, Nature has worked out some of her pleasantest and also some of her most cunning contrivances. The alimentary system of a motor cycle will swallow a corroding acid with the same indifference as a high-grade oil. That is not so with the human machine. At the beginning of the human alimentary system are

placed "taste-buds" which sample every particle which crosses the lips; messages are instantly dispatched to both higher and lower nerve centres in the brain and brain stem, keeping them in touch with what is happening in the mouth. Even before the food has passed the lips it has been sampled by the nose and smell messages have been dispatched to the brain, where they and the taste messages mingle and help, if they be agreeable, to give rise to that feeling we name appetite. The minute taste-buds, the transmitting stations for taste messages, are scattered on the upper surface of the tongue, chiefly towards its hinderpart, its base or root. The juices of the food in the mouth actually penetrate the coats of the taste transmitters and dispatch their messages, apparently by means of chemical reactions. The taste-buds are placed on the tongue because in chewing and swallowing they are thus brought in full contact with everything taken into the mouth. In the mouth food is wholly under our control; when it enters the throat or pharynx, as happens when we swallow, it passes into the charge of a machinery over which we can exercise no influence. It is on the threshold between the mouth and pharynx—between the voluntary and involuntary chambers—that Nature has planted the most powerful of her taste transmitters; the majority are placed on the root of the tongue, on the edge of the threshold; some also on the palate or lintel of the doorway. Before we can fully relish the taste of food it has to pass the threshold which takes it from our control. Nature, you see, has made as certain as is possible that fuel for the human machine will be used and not abused.

The appetite of a motor cycle is strictly limited by the size of the petrol tank and the dimensions of the jet aperture in the carburettor. An indicator tells the driver, as he fills the tank, when the limit of its capacity is reached. The human machine has also its indicator; when the stomach is filled there rises over us a feeling of repletion, but the exact mechanism which gives origin to this feeling is not yet understood. The stomach is not a rigid chamber, we

shall see, like a petrol tank ; its walls are built of living muscle which can relax as well as contract. Its capacity and power to waste can be increased by force—just as pressure could be brought to bear on a petrol tank, so that oil is forced within the engine cylinder to a wasteful extent. In the designing of the human machine Nature has exercised a degree of care for our welfare which may well be called grandmotherly. She has set up the contrivance called appetite to regulate the consumption of fuel to the needs of the body. We may circumvent her designs and enjoy life for a time by flooding our combustion chambers with a wasteful supply of fuel, but sooner or later she levies a fine on the exchequer of our health.

We are now to commence a rapid survey of the various chambers or workshops—the mouth, stomach, duodenum, small bowel, and great bowel—in which tissue-fuel is prepared from the food which is passed through them. These workshops, we shall find, are linked together by a well-managed transport system, designed on a plan quite different from any employed by man and yet regulated on the same lines as a modern railway system, except that the traffic is all in one direction, from lips to vent. The length of the system varies from one moment to another; when one section is shortening another may be lengthening ; but taking an average condition in a man of medium build, the total length may be estimated at about 28 feet. As the food makes this long journey, which it usually does in the course of from twenty-four to thirty-six hours, it passes through a series of elaborately fitted and busy factories, and undergoes many changes before the essential fuel becomes separated from the dross or refuse.

None of the factories set along the alimentary tract of the human machine is more effectively contrived than the first work-shop—the mouth. There are two doorways : one is guarded by movable muscular shutters or lips ; the other is seen when the mouth is widely opened leading into the throat or pharynx. The doorway to the throat is opened and closed by delicately adjusted side curtains—the movable pillars of the fauces. When we

eat, the faucial or palatal curtains are pulled tight; when we are about to swallow they are thrust aside and the bolus of food enters the pharynx. The floor of the mouth, as everyone knows, is moulded to form the tongue, a plunger or piston into the substance of which is packed a complex set of muscular engines. When these are set in action they can alter the tongue to any shape and move it in any direction. In the front part of the floor of the mouth the tongue is tied to the lower jaw—a lever shaped like a horseshoe. The jaw projects in front to form the chin, then passing backwards on each side of the floor of the mouth, bends upward to reach its sockets in front of the ears. When the mouth is used as a mill, as is the case when we chew, the tongue serves as a feeder to pass the food between the upper and lower teeth or millstones; when we use the mouth as a force-pump—as when we swallow—the tongue acts as a force-piston; if the mouth is used as a suction-pump, which is the case when a baby draws milk from the breast, the tongue again serves as a piston—a suction-piston. In speech the tongue modifies the shape of the mouth to meet the requirements of the voice.

Thus in the mouth many operations are carried on, but the one with which we are most concerned at present is the breaking down and grinding of food, thus preparing it for transport to the second factory or stomach. It is a very long time since man discovered he could save himself much personal trouble by grinding his food outside the body, and thus lessen the toil of working the mill with which Nature had provided him. Any pair of flat stones answered his purpose. One served as a nether millstone; it was fixed in the ground. The other, the upper, he worked by hand until he learned how to shape and fix it so that it could be turned by an engine. But in his various designs he always made the upper millstone the movable one. Nature had adopted an opposite plan. On the upper jaw, which is fixed in the face and forms a bony roof for the mouth, she set, in a half-circle, sixteen teeth to serve as cutting or grinding stones; the upper

jaw with its teeth serves as the upper millstone. The lower jaw, with a corresponding series of teeth, forms the lower millstone. The lower millstone is made to work on the upper, not as one wheel revolves on another but by means of a lever to which four pairs of strong engines are yoked—the muscles of mastication. They can move the lever on which the millstones are set in any direction, so that the teeth may cut or grind or do both at the same time. The lower jaw is used by the muscles of mastication as a lever of the third order ; the food between the teeth represents the resistance to be overcome—the load ; the two sockets, placed in front of the ear passages and in which the lower jaw moves, provide movable fulcra ; the muscles, which obtain a fixed basis on the skull, are linked to the lever between the teeth and the movable fulcra. The muscles of mastication are furnished with the usual elaborate intelligence service, and are thus kept informed not only as to what is happening in the mouth, but as to what is taking place in their own engines and in those of their partners and opponents.

An engineer builds a mill according to the dimensions laid down in his plans ; his machinery is of full or adult size from the beginning. Nature had to design the mouth so that it would serve the needs of a living body which keeps changing and growing for twenty years or more. All alterations and additions have to be carried out while the factory is in full activity. The bony scaffoldings which carry the upper and lower millstones have to be extended at exactly the same rate so that the fit and contact of the stones remain perfect at every stage of growth. The stones or teeth, however, have to be of full size when they come into use, for, once laid down, they cannot be altered. The grinding or cutting surfaces of teeth cannot be extended or renewed ; teeth which will fit a child's mouth are too small for an adult jaw, and an adult's teeth are too large to be placed in a child's mouth. Hence Nature's contrivance of two sets : a set to serve the needs of childhood, and another of larger make to replace them as childhood is passed through and adult

years are reached. By the commencement of the third year a child has got its full set of teeth—twenty in all, ten upper and ten lower. Even then there is being prepared at their roots a set which is to replace them and in addition twelve others, which will duly come into place as space is provided behind the milk set. Army manœuvres which able generals carry out in the field are often complicated operations and difficult of execution, but no army movement can rival the manœuvres which are to be seen in the mouths of well-grown children where little white soldiers rise up one by one, in the right place and at the right time, to form the upper and lower serried ranks of teeth. But teeth and jaws have fallen on times which, for them, are out of joint. They were designed to do all the milling man required; nowadays steam-driven machinery and high-class cooking have relieved them of the greater part of their work. We have seen that bone-builders lay down levers according to the stresses and pressures which fall on them when the human machine is in full action; the bone-builders of the jaws which make up so large a part of our face, have no longer falling on them the stimuli which arise from strains and stresses because their work is being scamped; the jaws are often ill built, the face tends to become long, narrow, sunken in, in place of being short, wide, and full. In olden days the teeth were often ground down almost to their sockets; nowadays, even after sixty years of wear, we may observe, in such of them as have survived the modern disease of caries, that their chewing surfaces are scarcely worn. Even the tooth-builders are affected by modern conditions; their workmanship is not what it was in prehistoric times. Nature is levying the fines she inflicts when her structures are unused.[1] Even with care, cleanliness, and the expert aid of dental surgeons it is difficult to prevent disease attacking our teeth. What, then, is to be done? Return to the diet of primitive men? In this case, as in many others, most of us will choose to reap such gains as invention brings within our reach and eat the food which modern skill has succeeded

[1] See Appendix K, p. 317.

in providing us with. For such gains we must be prepared to pay a price. The price is a daily attention to the toilet of the teeth, and even then we may not escape Nature's penalty.[1]

There is one other important operation carried on in the mouth which has yet to be mentioned. The moment food is placed within it saliva begins to be poured in from three pairs of factories or salivary glands. Two of these pairs are placed below the floor of the mouth ; the third is situated within the cheeks, immediately in front of the ear passages. The salivary factories may be set to work by the mere sight of food ; the sight of a bone will make saliva trickle from the mouth of a hungry dog. In this case messages have streamed in by the eye and reached certain exchange stations in the central nervous system, whence orders have been sent out which set the saliva producers at work. At the same time their blood supply is turned on. The usual messages, however, which bring about a flow of saliva in the mouth are dispatched from minute transmitters or receptors placed over the tongue—particularly in the taste buds ; but touch transmitters, which are very abundant in the mouth, may also be used. The urgency and nature of the messages determine the quantity and quality of the saliva poured out. Beneath the red membrane which clothes the lips, also under that which covers the tongue and lines the mouth, there is placed an under-carpet of minute glands. From these glands there issues a fluid which moistens the lips and lubricates the mouth. Thus as the food is masticated it is mixed with saliva, which not only helps in its reduction by the teeth, but has also a solvent or digestive action upon it. But, above all, the chief use of saliva is to reduce the food to a moist pulp. Such a consistency is necessary for its transmission from chamber to chamber by the peculiar transport system of the alimentary canal. When the necessary consistency is reached, there is a momentary cessation of chewing movements ; the lower jaw becomes fixed against the upper ; the mouth then acts as a force pump, its piston

[1] See Appendix K, p. 317.

or tongue forcing a prepared charge or bolus of food from the mouth through the threshold of the pharynx, where it is launched on its journey to the second alimentary factory or workshop—the stomach.

Just before closing this account of the various operations carried on in the mouth, there is one other matter which requires emphasis. We touched upon certain of the nerve stations which are scattered over the surface of the tongue and mouth and from which taste and touch messages are dispatched. There are also those end stations which keep the central nervous system informed as to the temperature of the food and drink as it enters the mouth. Mention must be made of still another system of nerve receivers and signallers, placed around the sockets of teeth and also within the pulp which fills the natural central cavities. From these dental nerve stations pressure messages are dispatched which keep the muscles of mastication informed as to strains and stresses which are falling on the teeth and from which they can regulate the amount of pressure to be applied. Healthy teeth seem to us to give rise to no sensation ; we are not conscious of messages arising in or near them. If, however, their pulps become exposed, then, as every one knows, they can be the source of excruciating messages. Here again we meet with another of Nature's methods of levying fines for neglect.

CHAPTER XVII

A TRANSPORT SYSTEM OF A PECULIAR KIND

In the preceding chapter we have seen how food is taken into the mouth, where it is pulped, rolled into suitable packages or boluses, and then by a piston-like action of the tongue the bolus is thrust within the pharynx where it is set out on a 28-foot journey, one which, under the most favourable circumstances, will extend over a period of at least 24 hours. In this chapter we are to follow the progress of a single bolus—the first spoonful of a dish of porridge of a peculiar kind, one known to modern physicians as a " test meal." It is mixed or impregnated with a tasteless, harmless salt of bismuth, and is given to patients when there is suspicion that the transport arrangements of their alimentary systems have broken down or become deranged. A bolus so impregnated is opaque to X-rays and hence its progress can be followed as it is carried from alimentary to alimentary factory, when the body of a living patient is transilluminated by the help of an X-ray apparatus. The bolus we are to follow in this chapter is to be dispatched at 8 a.m. prompt from the mouth of an accommodating friend. We are to have at hand not only the outfit to illuminate his body and so watch the meanderings of the bolus-shadow, shaped like an overgrown tadpole, as it is transported along his alimentary tract, but we shall also have at our disposal actual examples of the machinery employed so that from time to time we may examine the various parts of the canal through which we have watched the bolus pass. We are to concern ourselves chiefly with the management

and regulation of the transport or traffic along the alimentary canal.

There is no need to describe how petrol is carried or transported from the petrol tank to the engine of a motor cycle. The petrol tank or stomach is set under the horizontal bar of the frame, well above the level of the engine ; gravity is the force which carries petrol along the feed-pipe, which we have already compared to the bowel of the alimentary system. If the fuel supplied to our bodies were as liquid as petrol and we kept ourselves always in the upright posture, then a transport system similar to that of a motor cycle would have met our needs. Gravity would have been sufficient to transport food along the 28 feet of tubing which forms our alimentary canal. If the passage of the food had to be delayed in certain sections or compartments of the canal, as we know it has, then this could have been accomplished by the use of a system of automatic stopcocks or float chambers. The food which has to be transported along the "feed-pipe" of the human machine cannot flow like petrol, but, as we have seen, is reduced in the mouth to the consistency of a semi-fluid pulp ; it cannot be made to flow along a system of collapsible pipes which are kept compressed tightly against each other, as bowels are in the abdomen ; rigid tubing is out of the question in the human machine ; every part of it, save the bony levers, must be supple. Nor can its posture be guaranteed ; a motor cycle can run only as long as the petrol tank is above the level of the engine, but the human machine must be able to work in every posture.

Engineers have frequently to design a system for transporting a semi-fluid pulp from one workshop to another, but they never have been able to copy Nature's means of propulsion. For such purposes Nature always employs a pump with muscular walls. We have seen the plan on which the heart is built, an elaborately fitted muscular pump for propelling blood through the vast capillary fields of the human machine. We can picture the principle on which the heart works by compressing

the ball of a rubber syringe with the fingers and palm of our hand. The manner in which the fingers close on the rubber ball illustrates the mode in which the muscular wall of the left ventricle expels its charge of blood. The alimentary canal of the human body is fitted from beginning to end to serve as a muscular pump. Everywhere its tube or pipe is clothed with two layers or strata of muscle arranged so as to be able to propel the contents of the tube from point to point along the whole course. Thus the engines which are used in the transport of food along the alimentary canal are microscopic in size and are stationary in nature, being built within the wall of the tube. They are muscular engines of a type we have not seen before. They are not shaped like cylinders, but taper at each end like a spindle (see fig. 38). They are tightly packed together, side by side, their tapering ends overlapping and interdigitating. The total number of muscle fibres or spindles involved in transporting a single bolus of food along the 28 feet of alimentary tract is uncountable, for although the total length of each engine spindle amounts to $\frac{1}{15}$th of an inch, their width is only $\frac{1}{500}$th. Taking an average piece of bowel 1 inch in length, with a circumference of 3 inches, a piece in which the two muscular coats make up a combined thickness of $\frac{1}{6}$th of an inch, an estimate will show that in this short segment there are about two millions of these tapering muscle fibres or engines. Thus for the transport of even a single bolus through such a short segment of the alimentary tract two millions of engines have to be set in motion, in a definitely co-ordinated sequence. Each has to be started and stopped at a certain phase of the movement. The effect is simple, but the underlying mechanism is highly complex. Is there any wonder that such a transport system should break down occasionally, and that its repair should tax the ingenuity of the physician to the utmost?

The exact manner in which these muscular fibres are co-ordinated in their task of propelling the meals we eat along the alimentary canal we shall see as we proceed;

meantime we return to watch a single bolus of bismuth-laden food propelled along the first stage of its journey, from the pharynx to the stomach. The model in whom we are to watch its transit by the help of X-rays is a man of medium but spare build; in him the bolus has to be carried a distance of 12 inches, $2\frac{1}{2}$ of which lie in the pharynx, $9\frac{1}{2}$ in the gullet or œsophagus. Even although we are watching closely when the bolus is shot by the piston-like action of the tongue into the pharynx, the exact nature of the first part of the act is so quick that we cannot be sure of what has taken place; but presently we see in the neck, behind the windpipe, the black shadow of the bolus set out at an almost snail-like pace, making about 2 inches per second. Then by turning our model round, so that we may look obliquely across the chest, we again detect the black shadow creeping slowly down in front of the backbone until the level of the diaphragm is reached. There it seems to hesitate and stop two, three, or more seconds, as if knocking at the door of the stomach for entrance. As a matter of fact it is knocking, according to the custom recognised along the alimentary canal; it is waiting for the lock-gates to open which allow it to trickle or creep into the stomach some eight or nine seconds from the time it leaves the mouth. Were there no muscular sphincter or lock-gates at the gullet or cardiac opening of the stomach, then every time we take a deep breath, or press upon the epigastrium, or stoop down to lift an object from the ground, our meals would be forced from the stomach towards the mouth. When the bolus enters the stomach, the cardiac doorway is again closed.

The transit of a bolus of food from the pharynx to the stomach, whether we watch it by X-rays or trust to our daily experience, seems so easy and expeditious that we are surprised, when we look at the construction of the pharynx and œsophagus, by the complexity of the machinery which has to be set in motion. We have seen (fig. 33, p. 135) that the pharynx is a busy crossing used by two streams of traffic—air traffic and food traffic.

The air or breath entering by the nasal aperture above leaves by the laryngeal doorway below. The nasal aperture is guarded by a valve-like movable curtain, the soft palate; the laryngeal doorway, as we have already seen, can be automatically opened and closed. Food and drink, when they enter the pharynx, cut across the air-way. They enter from the mouth through the faucial threshold, which is guarded by the movable pillars of the palate; they leave the lower end or bottom of the pharyngeal bag by an aperture leading into the œsophagus, which is guarded and kept shut by a muscular stopcock mechanism known as a sphincter. The regulation of traffic in the pharynx has been compared to a police-controlled crossing in London. When a Royal procession is to pass through the city, the police, at a given signal, stop ordinary traffic and give the procession a free passage. At meal-times the pharyngeal police hold up the ordinary breath traffic and give the food and drink an open way. With the arrival of each bolus the nasal and laryngeal gateways are shut, and only reopened when the bolus has entered the œsophagus and the doorway through which it has passed has again become closed. Such a picture of the pharynx, while expressing certain truths, gives a false conception of the mechanism involved. The pharynx is a muscular force-pump for pressing its contents of food or of drink into the œsophagus as quickly as possible. The muscular sheets which are placed within its walls are made up of cylinders exactly like those of the voluntary muscles of our limbs; they are richly provided with nerves, some for conveying messages from the brain to the muscles, others for carrying messages in a reverse direction. Yet we cannot set the pharyngeal pump going by a direct effort of will; we must first perform a piston-like movement with the tongue as if we really intended to swallow something, and only in that way can we set the pharynx going as a force-pump. Tides of air may cross and recross the pharynx as we breathe without setting the pharyngeal pump into motion, but the instant that a bolus of food or a mouthful of water enters it,

then we find that the nasal and laryngeal apertures are automatically closed and the pharynx at once contracts and acts as a force-pump. As it passes into action not only are the breath openings closed, but at the same time the pillars of the fauces shut the doorway to the mouth, while the sphincter at the orifice of the œsophagus relaxes, thus leaving a single passage of escape for the contents of the pharyngeal force-pump (see fig. 37).

In the contrivance of the pharynx we have one of the most remarkable examples of Nature's reflex or "touch-the-button" mechanisms. Modern life has made us familiar with inventions of this kind, but they were discovered by Nature long ago. We press a button at the door of a high building, thereby setting an electric current flowing and a bell ringing in a chamber in its upper storey, with the result that a bolt is drawn and the door opens to let us enter. In the hall we find a lift or elevator provided with a row of buttons—one for each storey. We press one, an electric motor sets the lift in motion, and we stop at the desired landing. The lining membrane of the pharynx is studded with "nerve-buttons" or transmitters. The breath passes and repasses without influencing them, but the instant a bolus of food, a mouthful of water, or the root of the tongue, which forms a piston for the pharynx as well as for the mouth, comes in contact with or touches them, then a stream of messages is thereby dispatched which flows upwards in the nerves until certain busy nerve exchanges are reached in the medullary part of the brain stem. From these exchanges relays of orders are issued which reach the muscular engines controlling the doorways of the pharynx ; those leading to the larynx, to the nose, and to the mouth are promptly shut, while the sphincter engine, which guards the opening to the œsophagus, is ordered to relax. At the same time the muscular walls of the pharynx are thrown into action ; the pharynx then becomes a force-pump ; all its openings are closed save one, and it is through that one that the bolus is forced within the upper end of the œsophagus. How essential the machinery of the pharynx is to life we

learn when we see men or women in whom disease ha damaged the controlling nerve centres in the medulla all attempts at swallowing end in choking and spluttering. The reflex or "touch-the-button" mechanisms of the

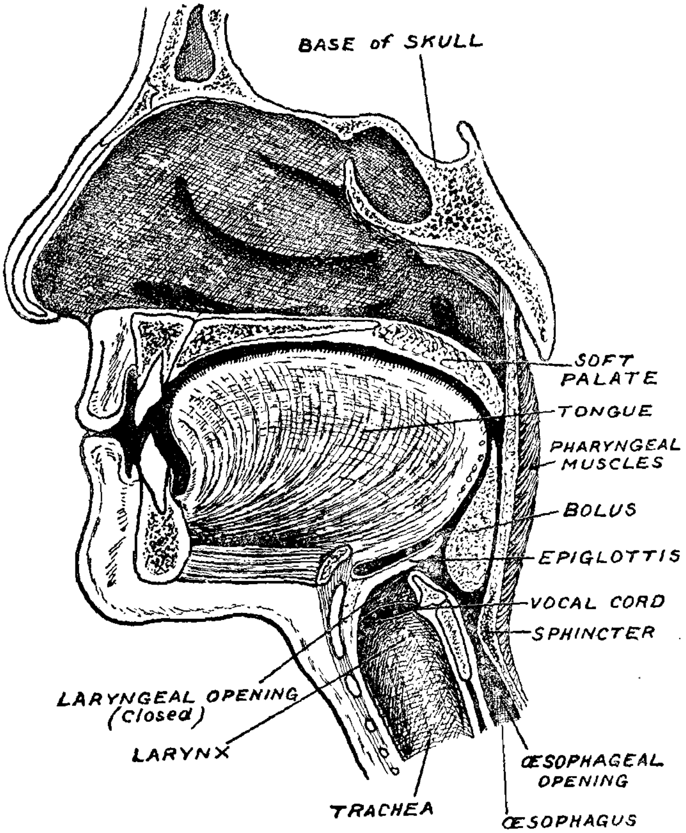


FIG. 37.—Diagram showing a bolus of food within the pharynx, in the act of being forced into the œsophagus.

pharynx have broken down. That such people may live food must be poured directly into the œsophagus by means of a tube attached to a funnel or filler.

A bolus of food is carried rapidly through the pharynx, but its transport in the œsophagus is leisurely. In fig. 38 a representation is given to show the manner in which the

œsophagus carries its load onwards. We are to see that it is a strange form of pump—a pipe-pump, making a wave of contraction which creeps along its muscular wall to serve the purposes of a piston. In our illustration part of the œsophagus has been cut open in order to show a bolus in transit. We have to deal with a muscular tube, 9 or 10 inches in length, lined by a loosely attached membrane. The muscular tissue is arranged in two layers or strata; in the outer layer the spindles are arranged in threads or bundles running along the tube

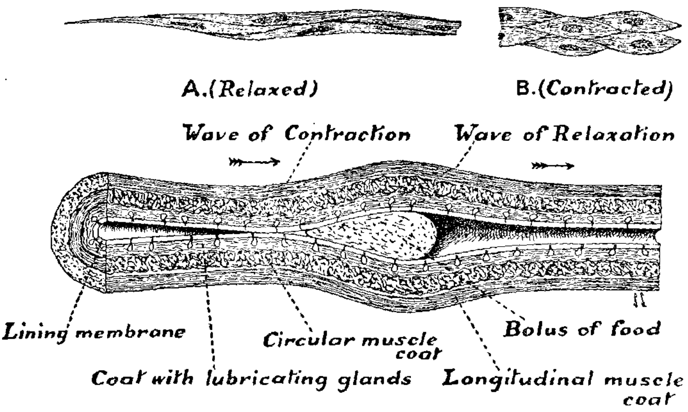


FIG. 38.—A segment cut out from the œsophagus and laid open to show a bolus in transit. A, a small fragment of the outer muscular coat magnified to show the individual spindle-shaped fibres of which it is composed in a relaxed state. B, fibres or spindles greatly enlarged to show a contracted state.

lengthwise; in the inner layer the fibres are arranged circularly, so as to form ring-shaped muscular engines. In fig. 38 a small fragment of the outer muscular coat has been magnified so that the individual spindles of which it is made up may be seen. Certain spindle engines have been greatly enlarged by the artist to show the change of shape when in action and when relaxed. No attempt has been made to depict the rich network of nerve fibres with which the muscular coats of the œsophagus are provided; by means of this network the myriads of muscle spindles of the œsophagus are harmonised in their work. From the network, nerve paths lead to and

from controlling centres in the medulla. But even when these pathways are cut, local mechanisms can still carry on transport duty, although indifferently. Then in the loose binding tissue, between the lining and muscular coats of the œsophagus, there are other nerves sending fibres to end in contact and touch transmitters and forming part of an elaborate touch-button machinery. In that same tissue, too, lie numerous little factories or glands for the production of a fluid to lubricate the lining of the œsophagus and facilitate the passage of food boluses. Nature forgets no necessary detail. Mention need hardly be made of the arteries and veins which maintain a steady circulation of blood through its capillary fields and supply the muscle spindles with oxygen and fuel and a means of carrying away their waste products.

We have been merely enumerating the parts of the œsophageal machinery ; we are now to see these parts in operation, transporting a bolus of food towards the stomach. The instant that a bolus has been pushed through the doorway leading from the pharynx and that doorway has closed, we see a ring of contraction form behind the bolus and commence to creep slowly downwards, forcing the bolus in front of it. The bolus on entering the œsophagus has touched a " button," and the ring of contraction is the result. As the bolus is driven forwards it comes in contact with a succession of such buttons, with the result that it is kept moving onwards. Not only so ; a ring of relaxation precedes the bolus and eases the passages. The ring of relaxation which heralds the advance of a bolus is, as Bayliss and Starling discovered, produced by the same touch-button mechanism as controls the propelling constriction ring. Every inch in the advance of a bolus means that millions of spindle engines have been duly started and stopped by an automatic controlling mechanism.

I have dealt rather fully with the transport system of the œsophagus because everywhere along the alimentary canal we shall find that a similar mechanism is employed. It is indeed a complex machinery representing many millions

of years of experimentation and invention on the part of Nature. She has forgotten nothing—not even the provision of means for the overcoming of a block or obstruction. As a result of disease, a narrowing or constriction may form at some point of the œsophagus—often just behind where the windpipe divides into the two bronchi—the passages to the lungs. When a contraction ring, which is urging a bolus onwards, finds that its load has stuck against such a constriction, it passes on and becomes dissipated. Presently another ring appears, more vigorous than its predecessor ; if it fails, another sets in and the effort is redoubled. Nothing could be more persistent than the attempts made by the muscle spindles ; the mechanism which controls their contraction is almost inexhaustible. We find, after a time of persistent effort, that the muscular coats have increased in thickness and in strength, the lubricating glands pour out their secretion more freely and abundantly. The human machine is one of these rare engines which develops a greater horsepower automatically as its load is increased. Muscle spindles have this power to a remarkable degree—more than any other tissue of the human machine. Often the nature of an œsophageal obstruction is such that their best efforts are vain.

Mention has already been made of the fact that, when the thorax is transilluminated by X-rays, a bolus can be seen to stop for a moment at the lower end of the œsophagus before being gently ushered into the stomach. That is because the passageway is there guarded and kept shut by a sphincter mechanism—muscular lock-gates, and as we shall meet several contrivances of this kind at other junctions of the alimentary system, we shall look at this one—the cardiac sphincter of the stomach—in some detail. As seen with the naked eye (see fig. 40) this sphincter appears to be a very simple structure ; it is merely a short segment—a ring—of the inner muscular coat of the œsophagus slightly strengthened. It differs, however, from the rest of the circular coat by being maintained constantly in a state of action or contraction.

When a bolus reaches the lower end of the œsophagus it sets a touch-button mechanism into operation, with the result that the spindle engines of the sphincter are thrown out of action ; the doorway is then open for the passage of the bolus. On its entrance, the sphincter again passes into action and remains so until the next bolus arrives. Here, then, is a small but wonderful machine—one which will remain on duty constantly for seventy years or more save for those brief respites it obtains during meal-times.

As we watch the arrival of the spoonfuls of the bismuth-laden test meal at the doorway to the stomach, we may see one bolus follow another so quickly that the first has not gained admission when the second arrives ; presently a queue forms filling up the lower part of the œsophagus. As long as the accumulation lasts the doorway to the stomach is kept open. Very rarely does the "touch-button" mechanism which controls the cardiac sphincter go out of order, but when it does there is a serious delay, and an accumulation of traffic in the lower end of the œsophagus. The "touch-button" mechanism works best with well-formed soft boluses of food ; tabloids or solid bodies, when they reach the doorway to the stomach, may fail to give the password that causes it to open. Hence such bodies may remain at the entrance to the stomach and give rise to strange and indefinite forms of pain which the sufferer may find difficult to locate. In other cases such arrested bodies give rise to hiccough.

CHAPTER XVIII

THE REGULATION OF A FACTORY FOR THE PREPARATION OF TISSUE-FUEL

We have dallied so long over the manner in which food is transported from the mouth to the stomach that the reader may well have forgotten the fact that we have a patient in front of us. By the aid of an X-ray outfit we are watching him as he consumes a pint of porridge impregnated with a harmless bismuth salt. He began at 8 a.m. prompt, and ten seconds later we saw the first spoonful enter his stomach, where it gradually spread downwards until it reached almost to the level of the navel or umbilicus. As bolus follows bolus quite a large shadow grows in the region above the navel—in the epigastric area, the lower border being rounded and rather irregular in outline, while its upper border, which continues to mount, is straight and level (fig. 39). It is evident that the stomach is filling, and at the end of ten minutes, when the dish is emptied, our friend informs us that he feels comfortably full. We know his stomach has not nearly reached the limit of its capacity ; it is an accommodating muscular organ into which two or three pints of porridge, or even more, can be safely packed, but it is full enough for our present purpose. No sooner has the food arrived than the stomach pulls itself together, as it were, and sets to work upon the part of the meal which has descended to its lower or pyloric part, thus lying near the exit or further gateway of the stomach—the pylorus. The stomach is merely a great dilatation or enlargement of the simple tube-like part of the alimentary

channel we have been examining in the previous chapter. In the stomach of our friend we can see the same kind of constriction rings appear and move; they do not begin at the upper end of the stomach, but below its middle part (fig. 39). We see one of these rings gradually form and then move slowly towards our

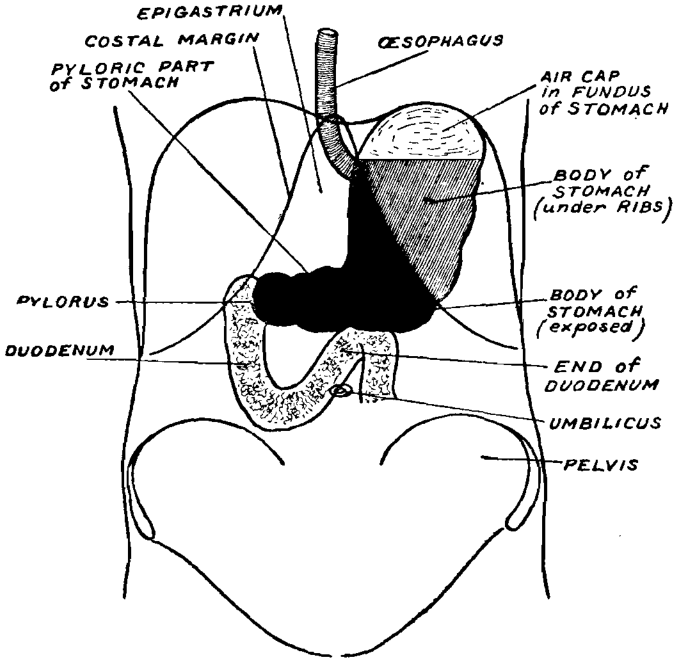


FIG. 39.—An X-ray shadow of the full stomach, with contraction waves passing towards the pylorus.

patient's right, thus approaching the pyloric gateway of his stomach. The constriction ring pushes in front of it a dilatation wave as if it were urging or milking the contents of the lower part of the stomach towards the pyloric gateway. We notice, too, that very soon after one wave has set out another begins almost at the same point, and pursues its forerunner at an orderly pace; there is a constant succession of these constriction waves; there may be as many as three seen in progress at the

same moment. In people with active digestions a contraction wave will appear every ten seconds, giving the stomach a beat or pulse of six to the minute, but three to the minute is quite a common rate. Clearly we are watching the transport system of the stomach at work—the system employed for passing food on from one to another of the chemical factories lying along the alimentary system.

When we observe what happens to the shadows of the contraction waves as they approach the pyloric gateway, we see that many of them become dissipated there and seem to have produced no other effect than mixing and pulping that part of the meal which is contained in the lower tubular or pyloric part of the stomach. But every now and again a wave is successful in forcing a little of the more fluid part of the pyloric contents into the third chemical factory of the alimentary system—the duodenum; after a successful wave we can make out a spray-like shadow formed by the ejected bismuth-laden material in the first part of the duodenum (fig. 39). Indeed very soon after the test meal reached the stomach these small, broken-up duodenal shadows began to appear, showing that the stomach begins almost immediately to discharge the more fluid parts of a meal. A glass of water taken before breakfast will, if the stomach is working as in health, be discharged into the duodenum within ten minutes or less from its being swallowed.

While these wave-like movements are in progress in the lower tubular part of the stomach, pulping and liquefying its contents, nothing is to be seen of them in the upper or main chamber. We may regard the upper part as a hopper or retort from which the lower or grinding part is fed. We notice, too, that the discharge from the pyloric part becomes accelerated after an hour or two; presently the shadow presented by the stomach becomes confined to its tubular part. By 12 a.m.—in four hours from breakfast-time—the whole of the meal will have been discharged if the stomach is working as in health.

The rate of discharge depends on a number of circum-

stances. A dish of cornflour will be passed onwards in the space of two hours or less, while a Christmas dinner of roast goose and plum pudding is likely to keep the discharge system of the stomach hard at work for three times that period. Youth, too, makes a difference ; in the young the stomach is vigorous and usually effective. In certain disorders of the transport system a new meal arrives long before its predecessor has been discharged. Twelve hours or more may elapse before its bismuth shadow disappears. The condition of mind, a feeling of well-being, has a direct and immediate influence on the transport system of the stomach. That digestion waits on appetite is a truth man has known since he became a thinking being. Indeed, the study of the movements of the stomach by means of X-rays and bismuth meals was first practised by Professor W. B. Cannon to discover how far the state of the brain could influence the work of the stomach. He was a student of Harvard University in 1896 when Röntgen's discovery was announced, and saw the possibility of studying the normal healthy stomach in a new way. He selected the cat as the subject for observation, and was the first to succeed in seeing the movements of the living stomach by means of X-rays. When the cat was made angry the movements of the stomach ceased ; when made to purr, they commenced and worked more vigorously than usual. Although the will can exercise no direct control over the muscular engines which carry on the transport system of the stomach, yet indirectly it can influence and play upon the elaborate nerve system which controls its movements.

In the meantime we must not lose sight of the main object we have in view—the preparation of body-fuel from the food we eat. We have seen how it is masticated and pulped in the mouth, and how it is transported to the stomach, and we have watched the shadow of that organ during the four hours in which its preparatory changes were going on. We shall now give our living model a rest, recalling him in the afternoon to see what progress the bismuth meal has made, and in the meantime

turn to an examination of the construction of the stomach —a preparatory factory for the production of tissue-fuel. In fig. 40 the stomach has been laid open to show its great chamber and its two doorways. The upper or

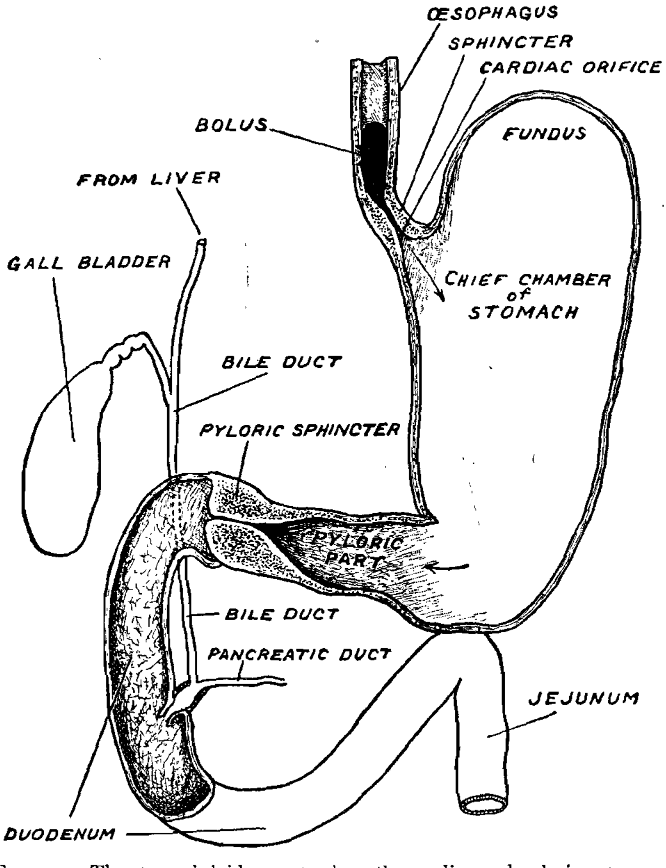


FIG. 40.—The stomach laid open to show the cardiac and pyloric gateways.

cardiac doorway, where the œsophagus opens, we have already seen to be guarded by a short sleeve of muscle—a sphincter mechanism. The lower or pyloric doorway leading into the duodenum (fig. 40) is guarded by the strongest sphincter in all the body, one always in action, only relaxing sufficiently to let the more fluid part pro-

jected by a contraction wave escape into the duodenum. We shall see that it is controlled by a most elaborate mechanism. We notice, too, that while one wall or border is short and runs straight from the cardiac to the pyloric gateway, a distance of four or five inches, the other is dilated or blown out so as to fill the left dome of the diaphragm and make a sweeping curve as it passes from one orifice to the other. It is plain that the stomach is merely a dilatation or expansion of a simple muscular tube, but it is not a uniform expansion; the enlargement affects only that side which forms the great curvature. Hence we are prepared to find that its flaccid but stout wall is made up, like that of the œsophagus, of two main coverings or coats—a thick inner lining, studded with minute chemical laboratories, and an outer muscular coat concerned with the pulping and transport of the food. The muscular coat is more intricate than that of the œsophagus because it has several duties to carry out. Its muscle spindles are grouped into three strata: in the outer the spindles are directed lengthwise and can shorten the chamber; the inner is circular and can make it narrow and long—it is the circular fibres which produce the contraction rings we have just been witnessing; the middle stratum has its fibres arranged obliquely in an intermediate direction. By the interaction of these three strata the stomach can be emptied and its shape altered according to requirements. In our drawing (fig. 40) no representation has been given of structures of the utmost importance—the arteries, veins, lymphatics, and nerves of the stomach. The stomach is profusely supplied with blood. Its lining membrane is flushed with a close-meshed network of capillary vessels, with minute test-tube glands—chemical retorts—stuck within the meshes of the capillary field; that field is fed by arteries which spring straight from the aorta; the blood from it drains into veins leading to the liver. Nerves stream into both lining and muscular coats from two sources: from nerve or exchange centres in the medulla, and from others set within the middle region of the spinal cord. There are

pathways for messages passing from the stomach to the nerve centres as well as from these exchange centres to the stomach. Messages are being constantly dispatched and received, particularly at meal-times.

Then there are its lymphatic vessels or lacteals, channels of a kind which are found in every organ, although this is the first reference which has been made to them. The tissues of the human machine are provided, as are the inhabitants of a modern town, with a sewage system. The refuse which escapes from the living units of the body tissues is gathered and carried away by special channels or vessels. Those of the stomach and bowel are named lacteals, because during digestion they carry a milk-like fluid called chyle, while in other parts of the body the fluid conveyed by them is transparent like water and therefore named lymph. The tissue sewage contains substances which can be again utilised in the body, and it is, therefore, not rejected from the system but poured by the thoracic ducts into the great veins as these approach the heart.

Although the stomach has all the outward appearance of being simply a soft-walled double-mouthed bag, yet when we look more closely it turns out, in reality, to be a great chemical factory. Food, the raw material from which tissue-fuel is prepared, occupies its great chamber ; into its wall are built not only the miniature retorts which are to furnish the solution or juice needed for chemical treatment of the food, but also myriads of microscopic engines which bring the retorts in contact with the food, and subsequently discharge such contents as are fit to be passed on to the next factory—the duodenum. When we begin a meal, even before food has actually reached the stomach, the miniature retorts all over the inner wall begin to manufacture and pour out a juice or solution that exercises a digestive action on the food exposed to it. The mechanism which sets secretion going is not of the "touch-button" kind, for food applied directly to the lining membrane of the stomach does not excite the flow of gastric juice. The nerve exchange which controls the

stomach is placed in the medulla, and the nerve messages which set it in operation are received from the mouth (nerves of taste), from the nose (nerves of smell), and from the eye (nerves of sight). It is strange that Nature should have adopted such means to set in operation the chemical factory which produces our gastric juice. She has, however, taken good care to protect her contrivance from abuse. For the controlling centre is fully excited only when there is need of food—when there is hunger and appetite. Hunger is the result of hard physical work, and therefore a price has to be paid in the form of labour before the stomach has sauce ready for another meal. There is, however, a further means which is employed for keeping up a flow of gastric juice—one which was discovered by Professor Edkins. When digestion of food has begun in the stomach a substance—we may call it a drug,—which is formed in minute amount within the lining membrane of the pyloric part of the stomach, is liberated and passes into the blood. This substance—gastrin—although it circulates all over the body, influences only one part of it, and that is the glandular inner coat of the stomach. It stimulates the minute glands or retorts to pour out the solvent needed for the digestion of food. Thus the stomach, so long as digestion and absorption is proceeding, forms its own stimulant.

One very large group of foods—the carbohydrate group: sugar, starch, and fats—are scarcely influenced by gastric juice. They are passed on to be turned into tissue-fuel in factories further along the alimentary tract. Its digestive force is spent on nitrogen-carrying foods —meats of all kinds: flesh, fish, fowl, egg, and milk. Those substances are dissolved so that they may be taken into the wall of the stomach, and thus passed on into the blood stream. They are not only made soluble, but they are also changed—split up into simpler chemical compounds, the first step in the preparation of, not tissue-fuel, but tissue-food. Carbohydrate foods provide tissues with the chief elements needed for the production of heat and work, but muscle-cylinders, bone-builders, and other

living units need also a nitrogen-carrying element for their maintenance. It is the preparation of this nitrogenous or proteid element which is the speciality of the factory we are now considering. The gastric juice works at and dissolves the outer stratum of the food mass in the stomach—the layer in contact with the lining membrane. The juice also penetrates the food contents of the stomach and prevents them from fermenting or going bad.

Why does not the gastric juice digest the lining membrane in which it is formed? John Hunter saw that it did attack and digest the wall of the dead stomach; also that it could not attack certain worms which live in the stomach until they were dead. When we say the lining of the stomach escapes being digested because it is living, or that it has developed an immunity to gastric juice, we do not explain the mystery of the fact; Nature has developed a protective mechanism of some kind in the gastric lining, the nature of which we do not yet know.

We now come to one of the marvels of the animal body. We have been speaking of digestion, but have said nothing of absorption—the passage of soluble contents from the cavity of the stomach to the rich capillary blood-field of its lining membrane. We know that certain substances pass through the gastric wall very quickly; we are conscious of the influence of wine within a few minutes of drinking it, so quickly is alcohol absorbed. Salts, certain poisons, and a percentage of some sugars also enter the blood through the gastric membrane, but starches, fats, and most sugars pass along untouched. Only a small proportion of the meat we eat—perhaps as much as a third—is dissolved and absorbed in the stomach; the remainder has to be dealt with further along the alimentary tract. The lining membrane into which these substances are absorbed is paved with microscopic living blocks—living units—which are constantly forming and throwing out mucus—a glairy lubricating substance which keeps the surface clean and moist. Everywhere the pavement is pierced by the

minute mouths of the test-tube glands—the microscopic retorts—which form the gastric juice. Through the living pavement the absorbed elements have to pass before they reach the capillary blood-field which occupies the spaces between the test-tube glands. It is not a mere physical process of diffusion ; the pavement units have a taste of their own ; gastric juice they reject, some fluids may lie in the stomach for hours and yet they will not touch them. Having passed the pavement barrier, the absorbed products are then really within the machine—if not a living part of it. In the blood they are carried straight to the greatest chemical factory of the body—the liver. There they undergo further preparation and also storage.

Having thus glanced at the chemical changes undergone by the food in the stomach, we return to consider a few of the more remarkable contrivances connected with the regulation of its transport system. We have already seen that the pyloric gateway is guarded by a sphincter and that it played the part of a cautious janitor in regulating the rate at which the contents of the stomach were discharged into the duodenum. If there were no janitor at the pylorus, the stomach would empty itself within a quarter of an hour or less of being filled, and thus throw the burden of its work upon factories further down the line, factories already burdened with as much work as they can overtake. When we look at the circular muscular coat of the stomach (fig. 40) as it passes on towards the pyloric gateway we see that it gradually becomes thicker, and then, when it actually reaches the pylorus, it rapidly increases to a great thickness, and at the same time its manner of action alters. The pyloric sphincter is always in a state of action or contraction ; the gateway is always shut. Then, beyond the pylorus, the circular muscular coat, as it passes on to the duodenum, becomes very thin and reassumes a normal state—one of relaxation. We notice that when the contraction waves which milk the contents of the stomach towards the gateway actually reach the sphincter, they cease ; they do not spread into

the duodenum. They are blocked at the pylorus. The pyloric gateway is not regulated by the usual form of "touch-button" mechanism; the opposite is the case. When a solid body is brought down and pressed against it by a contraction wave, the sphincter closes the gateway more tightly. As far as we yet know, it can be manipulated only by chemical messages or signals. When the gastric juice is plentiful and markedly acid in quality it yields to the contraction waves which beat against it and allows a jet of gastric contents to pass. But when the acid contents have thus freely entered the duodenum, the sphincter again becomes recalcitrant and refuses further passage from the stomach until the duodenal contents have become neutralised and alkaline in reaction. Thus is the pyloric sphincter automatically regulated by the chemical state of the contents of the stomach on the one hand, and the readiness of the duodenum to receive a further load on the other. The pyloric janitor is also controlled by signals which may arise from other factories further down the alimentary line. It is manifest, if these factories, such as segments of the small bowel or the cæcum or a part of the great bowel, are already overtaxed, that an addition to their burden may lead to a complete break-down. Hence, by some system of signalling we do not rightly understand, they can influence the pyloric janitor to keep the gateway of the stomach closed and thus delay the passage of its contents. Sir Berkeley Moynihan discovered, in connection with disease of the cæcum and appendix, that if these parts are inflamed they take control of the pyloric janitor. To the superficial observer of such patients, the stomach seems at fault; they blame it for holding up its contents, and their first thought may be to force it to work by applying strong medicines, thus bringing about the very condition which Nature is trying to prevent by means of an ingenious mechanism.

There is also another matter which must be touched on here—one which was skimmed over when speaking of the heart. We saw that the contractions of the ventricles,

which give the pulse-beat, took place at a rate of between 72 and 80 a minute. How is the rate of the contractions regulated in the heart? The stomach, as we have already seen, has also a pulse—one which beats at from 3 to 5 times a minute. In the ventricles of the heart the wave of contraction is so quick that to our eye it appears to involve the whole of both chambers at once. Careful measurement, however, shows that there is really a wave which spreads over the ventricle—much as a train of gunpowder is fired when a match is applied to it. In the stomach contraction waves spread slowly and in one direction; we can see them very distinctly because they are not hurried. Now, in the heart we know that the contraction waves arise at one point—a nodal point—just as an exploding train of gunpowder spreads from an ignition point or percussion cap. Nodal points seem to serve as percussion caps for starting waves of contraction. There is in the muscular coat of the stomach, near the œsophageal opening, a patch of tissue which serves as a nodal point for starting the contraction waves of the stomach. These become visible and marked when they reach the pyloric part of the stomach. They are produced slowly, only 3 to 5 a minute. Thus the stomach, as well as the heart, has a regular beat or pulse, and so, we shall find, have the other parts of the alimentary tract.

Nature in her contrivances has considered not only our daily needs but has extended them to the exigencies which arise from abnormal or disordered conditions. She has elaborated a nerve centre or control exchange which, on the receipt of messages of distress, can actually empty the stomach. The vomiting centre can take charge of the musculature of the stomach and not only reverse its action but also bring into use all the muscles of the body which are accessory to the act of vomiting—the diaphragm, the muscles of the œsophagus and throat,—and thus by a combined effort empty the stomach of its contents.

The vomiting centre is accessible to messages from nearly all parts of the body. They may arise from the womb, from any part of the bowel, stomach, or throat.

They may accompany disease of the brain, especially of the cerebellum, the chief centre of the balancing mechanism of the body. Hence, too, disturbances of balance, such as result from the movements of ships or of swings, give rise to vomiting. But why the balancing mechanism should be so closely linked up with the stomach is a matter which has never yet been satisfactorily explained.

CHAPTER XIX

THE BIGGEST AND BUSIEST FACTORY IN ALL THE BODY

THIS chapter begins at 2 p.m. ; it is now six hours since our friend supped his bismuth breakfast. No sooner was it swallowed than the stomach began to discharge the meal in minute jets as if its essential purpose was to serve as a hopper for feeding a mill placed further along the alimentary tract. Food, we have seen, does undergo certain preparatory changes in the stomach ; a small amount is absorbed. The chief use of the stomach, however, is to store a sufficient supply of raw fuel to meet the needs of the human machine for a limited number of hours. In England we usually load it to serve our needs for a period of four or five hours, but habit will accustom it to big meals at long intervals or small meals at short intervals. The stomach, like all organs of the body, can be made to accommodate and regulate itself to circumstances. But whether its loads are big or small, seldom or often, it always seeks to keep up a slow and constant discharge of its contents as if that were an essential part of its duty. That indeed is the case, for the mill it feeds is the biggest and busiest factory in all the body, and can deal at one time with only minute quantities of the raw material, or chyme, supplied to it from the stomach. It is this factory we are now to investigate, one stretching along a tube-like corridor for a distance of 20 feet—one fitted out with all the appliances needed for the conversion of the raw materials contained in food into the finished products which are consumed in the tissues of the body. The small bowel is the essential factory of the alimentary system.

When we now examine our friend to see how his breakfast has progressed, and which has now been under way for six hours, we observe appearances which bewilder us at first. Within an extensive area of the lower part of his body, from the region of his stomach above to deep within the pelvis below, we see scattered everywhere small, flecked, broken-up shadows, like thin wispy clouds which veil the moon. There is no hurry or scurry amongst them ; their grouping changes slowly, almost imperceptibly ; here and there we may note a sudden movement ; at times we notice a shadow break up or a fresh one gather. But there is no drift in any decided direction. The stomach, as we have already noticed, had become free from all traces of bismuth two hours before. The first part of the small intestine or bowel—the U-shaped duodenum (see fig. 39)—we still see marked out by an almost continuous band. The only other fixed shadow is found in the right side of the belly between the navel and the right hip-bone. Here we see the bismuth breakfast accumulating in another chamber or factory—the blind sac or cæcum which forms the first part of the colon or great bowel. With some manipulation we can make out a pencil-like shadow passing from the cæcal shadow towards the pelvis, which tells us that bismuth-laden material is entering the worm-like appendix of the cæcum (fig. 43).

We notice, too, another well-marked shadow approaching the cæcum from the pelvis—the loaded end of the small bowel. The appearance gives the impression that the bismuth-laden chyme finds some difficulty in obtaining entrance to the cæcum. So it has, for its passage is guarded and regulated by anothor janitor or sphincter mechanism—the ileo-cæcal sphincter, so called because it lies at the junction of the lower part of the small bowel or ileum and the cæcum (fig. 44B). It might well be named the ileal sphincter, for its chief use is to regulate the passage of the ileal contents from the ileum to the cæcum. But it does serve another purpose; however vigorously we press on the cæcum we cannot press its contents into

the ileum; the ileo-cæcal sphincter is an efficient door-keeper and prevents any reflux; once the chyme is in the cæcum, there is no turning back, unless the mechanism has become disordered. The sphincter marks the boundary line between two distinct alimentary factories; the one we are now considering ceases there.

It is very likely that if we had examined the cæcal region of our friend's body at midday, by which time the stomach had discharged its contents, we should have seen the advance guard of the bismuth breakfast then reaching the cæcum. The intestinal journey of 20 feet takes about four hours—240 inches in 240 minutes, an average pace of an inch a minute. If we have patience and continue our examination we shall see the rear-guard of the meal reach the cæcum somewhere between 4 and 5 o'clock—about tea-time—if our friend's system is regulated as in most healthy people. By tea-time the bismuth breakfast—or what is left of it—will have reached the cæcum. What happens to it there we shall discover in another chapter. Meantime our business is to see what changes have taken place in the bismuth meal during its four or five hours' sojourn in the intestinal factory.

Before proceeding to examine the complex mechanism of the human intestine it will repay us to spend a moment on the simple intestinal machinery of a motor cycle. One of our main aims is to follow out in detail the correspondence of parts in a locomotive machine planned by man and in one designed by Nature. We have identified the feed-pipe which conveys fuel from the petrol tank to the carburettor of the engine, as the part which serves the same office in a motor cycle as the bowel does in the human machine (fig. 1). We were careful to point out that, as petrol is a prepared fuel and already fit for internal combustion, the feed-pipe had merely to play a passive mechanical part. The feed-pipe which could truly be compared to the bowel would be one designed for a motor cycle which was built for the consumption of a bituminous shale, one containing the raw materials from which a combustible oil could be manufactured. A

motor cycle of this kind would require the alimentary outfit of a human machine—a mouth with jaws to crush the shale, a stomach or tank to hold a reserve store sufficient to serve for a single journey, and a bowel or feed-pipe which is capable of manufacturing a combustible oil from the raw materials in the shale. The stomach or store tank must be fitted with a sphincter mechanism to regulate the discharge of its raw contents into the feed-pipe, just as is the case in the human machine. Within the feed-pipe must be fitted up all the chemical apparatus needed for the conversion of the raw products in the shale into a diffusible combustible oil. The interior of the pipe must be so made that it will immediately imbibe or absorb the oil as it is formed and pass it on to the circulation of the engine. A vent for the refuse or excrement would have to be fitted to the feed-pipe, just as is the case in the human machine. It is only when one works out such a comparison that a full realisation is obtained of the wonders which Nature has masked in the intestine by giving it all the outward appearance of extreme simplicity. Few people think of a sausage skin as the husk of a living laboratory in which chemical miracles went on all day long.

Before we begin an examination of the construction of the intestinal factory, we shall save time and make our task easier if we first glance at the nature of the work which has to be carried out in it. The chyme, as it enters the duodenum from the stomach, has already assumed the consistency of a fluid. The raw food materials thus brought into the intestinal factory for treatment fall into three main groups. The first and chief group is made up of starches and sugars. They have to be reduced to a kind of sugar which can be absorbed and used within the body. These substances are prepared or reduced by having molecules of water forced into their composition. The wedge which Nature uses for driving water molecules into starch is named amylopsin—a ferment or enzyme, of which a very minute quantity is effective. One of the businesses carried on

in the intestine, then, is the manufacture and production of this starch-reducing substance. The nitrogen-containing elements in the chyme have also to be dealt with. The nature of the change worked by the intestine on them can best be made clear by the use of an illustration. We take wool from the sheep and make it into clothing for our own bodies. When the cloth has become worn we may weave it again, but before that is possible we must tear the cloth to fine shreds—reduce it to the condition of shoddy—before it can again go to the loom. That is what the intestine has to do with the albuminous articles of our diet. They are composed of huge complex molecules built up in the living bodies of animals and to a less degree in the seeds of plants. The intestines have to split up these great molecules—reduce them to "shoddy" so that they may again be woven into the texture of the living tissues. We saw that the process of reduction or digestion was commenced in the stomach; it is continued and carried to a further extent in the intestinal factory. The bowel is a shoddy mill, but the means employed are chemical. Nature again uses one of her miraculous wedges—a ferment or enzyme named trypsin. The manufacture of trypsin is another industry carried on in the bowel. Then there is a third important element of our diet—fats. Everyone is aware that fat forms the basis of soap and that soap can be dissolved in water. The intestines convert fat to form a soap by the use of a special ferment or enzyme—lipase. The manufacture of lipase is another industry carried on in the intestine. By the use of these enzymes the raw materials of our food are reduced to a condition which makes them suitable to be used as body-fuel.

The juice which contains these digestive enzymes is formed from the blood by living microscopic units. Along the whole length of the bowel these units are grouped so as to form minute test-tubes which are packed closely together side by side, with their mouths opening on the surface of the lining membrane. The lining membrane, in which the test-tubes are set, is per-

meated by a close-meshed capillary field. The blood which flushes the network of capillaries not only supplies the tubes with the materials needed for the production of the digestive juice, but is also conveniently placed for absorbing the finished products of digestion. Lymph spaces and vessels which are drained by the lacteals also abound in the lining membrane (fig. 42).

The small bowel thus consists of millions of minute test-tube factories spread out on the interior of a soft-walled pipe, extending to a length of 20 feet, or more, in a fully-grown man. It is manifest, however, that the process of preparation would be assisted if a free supply of digestive juice could be added to the chyme as soon as it has entered the intestine. For this reason an outgrowth or annex has been formed from the duodenum—one composed of units which produce ingredients essential for processes of intestinal digestion. In this way a special factory—the pancreas or sweet-bread (fig. 41)—has been established. In the course of a day it produces considerably more than a pint of secretion. The pancreas is set into action by a simple mechanism which was discovered some sixteen years ago by Professors Bayliss and Starling. Other observers had noticed that the flow of pancreatic juice began as soon as the acid chyme from the stomach came into contact with the lining of the duodenum. It was known, too, that no "touch-button" mechanism was involved, for the flow could still be started even if all the nerves to and from the pancreas were divided. Professors Bayliss and Starling guessed that a new kind of machinery was set in motion by the acid chyme coming in contact with the lining membrane—a chemical machinery. They found that the contact of acid caused the lining membrane of the duodenum to form a minute quantity of a substance they named secretin. Secretin acts as a missive or letter; it is posted in the blood and carried round the body until it reaches its proper address, namely, the pancreas. There it sets the enzyme-producing factories at work and at once produces a flow of pancreatic juice which is

collected and poured into the duodenum by a special system of ducts. We shall come back again to this remarkable example of a postal system—a system which is widely employed in co-ordinating the work of the human machine. Acid chyme not only sets the pancreas working, but, as we have already seen, causes the pylorus to shut, thus preventing any further addition to the duodenum until the pancreatic juice has neutralised the

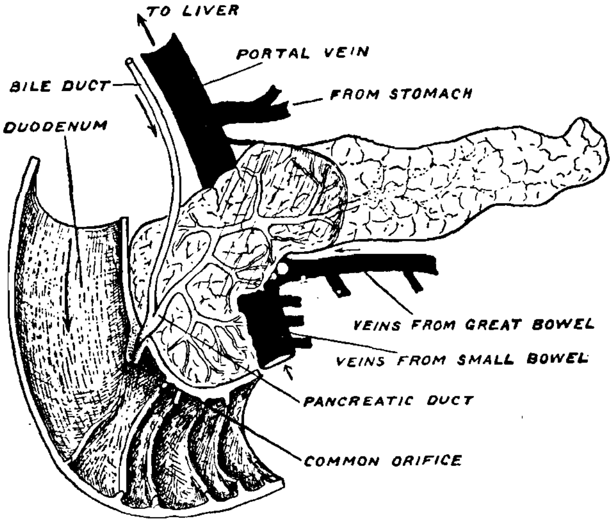


FIG. 41.—Part of the duodenum, with pancreas and bile duct.

preceding batch of chyme. By this simple mechanism Nature has contrived to regulate the flow of chyme from the stomach according to the rate at which the pancreatic juice is able to deal with it.

The arrival of chyme in the duodenum not only sets up an activity in the pancreas but also in a neighbouring chemical factory—the largest in all the body—the liver. It, too, represents an outbuilding or outgrowth from the bowel. At a very early stage in the formation of the human body, when the embryo is little over a quarter of an inch in length, we can see the liver being formed by a bulging out of the duodenal wall. The living micro-

scopic units, of which the liver is made up, were originally placed in the wall of the bowel and were concerned in—not the production of digestive juices, but the elaboration of body-fuel absorbed from the chyme. Instead of being placed all along the bowel these units have been collected in one mass—the liver (see fig. 25, p. 92). In the liver they are able to deal with elements absorbed from the food while on their way to the general circulation of the body. All the blood from the alimentary tract is gathered by the portal vein and poured into a spongework of capillary vessels which permeates the liver. The living units there deal with the products of digestion before the portal blood joins that of the general circulation. The liver is a great chemical laboratory in which the products absorbed from the bowel are turned into substances which are ready for consumption by the tissues of the body. The reagents employed are ferments or enzymes; all are manufactured in the living units of the liver. The liver serves not only as a laboratory but also as a storehouse. The derivatives of starches and sugars—carbohydrates—are stored within it in the form of glycogen. When the body tissues are in need of fuel the liver changes the glycogen to blood-sugar and sets free the amount required in the circulating blood.[1] The liver also deals with the products derived from nitrogenous foods. It is during their preparation that urea is formed as a by-product. That, too, is thrown into the blood stream, from which it is extracted by the kidney and then discharged from the body. In the course of the many chemical operations carried on in the liver there are other by-products which are not returned to the blood, at least when the liver is acting normally, but are collected and discharged into the duodenum by a system of ducts as bile or gall (fig. 41). A special reservoir—the gall-bladder—is attached to the main bile duct, but in all stages of digestion it is full (fig. 40). Nor do we ever find it empty; its real use is an unsolved puzzle. The bile has no direct digestive action on the chyme, but it has an important influence on the fats contained in it, breaking them up into an emulsion and

[1] See Appendix L, p. 321.

thus preparing them for their conversion into soaps. If the biliary function of the liver is deranged the bowel experiences a difficulty in the digestion of fats. The secretions of the liver and pancreas enter the duodenum by a common orifice, which is guarded by a sphincter mechanism (fig. 41). The bile and pancreatic juice, fully a pint of each are formed daily, enter the duodenum and become mixed with the chyme as it enters the great intestinal factory.

Having thus made a rapid survey of the means adopted for the digestion of chyme, we now turn to the system of transport which carries the chyme along the intestinal tube. The system is one with which we are already familiar. There are the usual two strata of muscle—an outer with the spindles arranged along the length of the bowel ; an inner with the spindles set in a circular manner. Between the muscular strata, and closely connected with them, is an elaborate nerve system, made up of nerve corpuscles or cells as well as of fibres. Inside the muscular coat is the lining membrane of the intestine, where all the operations connected with digestion and absorption are carried on. Outside the muscle coat is a covering membrane—the peritoneal coat. This is perfectly smooth and moist, in order that one loop of bowel may move upon an adjoining loop just as freely as one worm may glide over its neighbour even when these are packed as units of a wriggling mass. Indeed, in one sense we may truthfully regard an earthworm as a moving independent miniature piece of bowel.

We have seen that the contraction waves which sweep along the stomach and milk its contents into the duodenum usually start from a particular centre or nodal point. There are nodal points in the bowel. There is a dominant centre in the duodenum above the entrance of the pancreatic and bile ducts, where contraction waves start at a rate of five or six a minute and slowly creep down the duodenum, milking its contents in front of them. Then, where the duodenum passes into the next part of the small bowel, the jejunum, another series of driving

or peristaltic waves commence which carry the liquid chyme slowly towards the cæcum. We have seen that the average rate of progress is only about one inch a minute.

These driving peristaltic waves, however, do not represent the true beat or pulse of the intestinal musculature. The chyme has not only to be carried along the bowel, it has also to be kneaded and broken so that new particles are being continually brought in contact with the living membrane. It is only by exposing fresh particles of chyme to the wall of the bowel that the digestive juices and absorbing surfaces can accomplish their purposes. Hence we find that the musculature of the bowel, besides being thrown into occasional driving waves, is always contracting rhythmically, as if it were a heart; constantly kneading and moving the chyme, and at the same time producing another but very important effect—squeezing the capillary field of the lining membrane and thus helping to drive the blood, laden with the products of digestion, into the portal vein and liver. Our health depends very greatly on the soundness and activity of the transport system of the small bowel. If the chyme stagnates, then it also ferments and putrefies.

The contraction waves always go in one direction—down the bowel. The mechanism which prevents them from passing in the opposite direction we are not quite certain of. There are nodal points at the beginning of the small bowel, and these, being more excitable than the musculature lower down, dominate the rest of the bowel and become the pace-makers of its transport system. Contraction waves, however, may become reversed. If an obstruction should occur in the passage of the chyme *then waves arise at the site of the obstruction* and sweep upwards, milking the chyme away from the point of blockage. That is Nature's mechanism for affording relief and at the same time producing the conditions which will permit a cure to be effected. Although the movements of the bowel arise within its own musculature, yet the central nerve system has access to it and can

alter and affect its movements. The stomach, too, has its own movements, but, as we have already seen, it also can be affected by the emotional conditions which may affect our brains. Grief can make the bowels yearn.

The arterioles which open into the capillary fields in the wall of the bowel are under the direct control of the special nerve centres which regulate the distribution of blood to the various parts of the body. During digestion the bowels are flushed with blood ; the stopcock mechanism of the arterioles is turned full on. In hard muscular exercise the opposite is the case ; they are turned off as much as possible so that all the blood available may be mobilised for the use of the body muscles.

Lastly, we have to consider the manner in which the products of digestion are absorbed from the chyme. Here we see Nature adopt a method or contrivance of a kind well known to engineers. In order to raise a head of steam in an engine as quickly and as economically as is possible, the heat of the furnace is carried through flues or pipes which are immersed in and surrounded by the water of the boiler. The engineer aims at bringing an extensive and thin sheet of water in contact with an equally extensive heating surface. In our lungs Nature has brought a film of blood 27 feet square against an equally extensive ventilating surface. In the small bowel an absorbing surface of 8 square feet is brought in contact with a constantly changing film of chyme. The absorbing surface is really greater than I have estimated, because of two circumstances. In the upper part of the bowel—the jejunum—the lining membrane is raised into crescentic folds which cross the lumen of the bowel and almost double its absorbing surface (fig. 41). Then there is from the beginning to the end of the small bowel a carpet of villi—miniature projecting fingers or tongues—over which the chyme has to flow. Villi contain extensions of the capillary blood-field and also a slip of muscle which gives them a power to contract and thus act as pumps. Within them, too, are the commencement of lacteal vessels. The absorbing surface may be about twice the

extent I have mentioned. In reality it probably amounts to about 16 square feet.

The interior of the bowel is paved with microscopic living blocks of the usual kind—mucus epithelium. The absorbing surface, which is formed by these units, must be kept fresh, moist, and lubricated. These conditions are secured by a constant formation of mucus in the paving epithelium. Its units or blocks are continually forming a fresh covering of mucus. But the paving

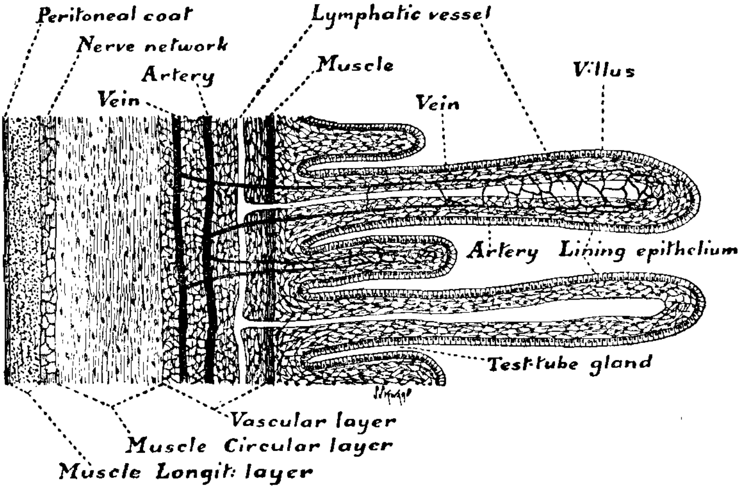


FIG. 42.—Section across a part of the wall of the small bowel showing the structure of two villi; the test-tube glands and lining epithelium are also represented.

epithelial units have much more important services to perform than merely keeping the surface fresh and lubricated; they are the agents which select the products of digestion, absorb them, and pass them on. They make the substances which are absorbed part of the living body. Those which come from starch foods or from nitrogenous foods are passed into the blood of the capillary field and are thus carried to the liver, but the soaps have a special destination; they are handed or directed to the lacteals, and have several filters to pass through before they are discharged into the great veins. Much, then, depends on

how the paving epithelium of the bowel does its work, and the manner in which that work is done will depend upon whether or not we ask it to deal with a greater amount of fuel than the body really needs.

There is a contrivance used by gold-miners which will help us to understand the essential mechanism of the small bowel. The rock or quartz which is quarried from the gold-bearing vein is ground to a powder by powerful batteries of stamps. Near the batteries is set up a tailrace through which a powerful stream of water flows. The bottom of the tailrace is covered with a carpet made of blanket, which we may look upon as representing the lining membrane of the bowel. When the crushed quartz is thrown into the head of the tailrace, the sand and particles of stone are carried away by the flow of water, but the grains of gold sink into the pores of the blanket and are held there. After the washing is over we find the blanket, towards the head of the tailrace, full of heavy gold grains; further down the gold particles are fewer and smaller; at the end none are to be seen; all the available gold has been absorbed before the wash reached the dump at the tail. Now, the bowel is a tailrace, 20 feet or more in length. The chyme is washed over it by the contraction waves which sweep down the bowel; it is continually stirred by the kneading waves. By the time the chyme has passed over the whole length of the bowel and reached the dump-head—represented by the cæcum—all the fuel which can be extracted from the chyme by ordinary digestive means has been removed. The residue which passes into the cæcum represents the washed tailings of the intestinal tailrace.

CHAPTER XX

A FACTORY THREATENED WITH DECAY

In the two preceding chapters we followed the shadow of a bismuth breakfast through two great living chemical laboratories ; in this chapter we are to trace the shadow of the same breakfast as it passes along the third and final chamber of the alimentary system—the great bowel. Our friend has been on his usual diet since last we examined him ; a light lunch which followed his bismuth breakfast, and a dinner taken in the evening were free from any substance which is opaque to X-rays ; his bismuth meal is the only one of the three which will throw a shadow. We are now to examine him in the morning following as he sits down to breakfast. Although twenty-four hours have elapsed, a dense garland-like shadow, appearing as if suspended within the cavity of the abdomen, shows us that the bismuth breakfast, or what remains of it, is still retained within the great bowel (fig. 43). The black outline of the great bowel is seen commencing at the cæcum in the right flank, ascending in the right loin, and then crossing the belly about the level of the navel. We can follow a twist which is made as the left loin is reached, where the shadow tapers almost to a pencil as it descends towards the left groin. The shadow swung across the belly is broken, as if composed of large jet beads strung on a string.

We saw the outline of the bismuth breakfast begin to form in the cæcum at mid-day ; by tea-time—nine hours after the meal was taken—all of it had passed into the great bowel. The lunch and dinner which followed this

breakfast have also passed through the small bowel at the usual pace, and were added to the bismuth-laden contents of the great bowel before bed-time. The "tailings" of a day's meal spend the night which follows in the final laboratory of the alimentary tract. In the second factory the intestinal contents were hurried along; but here, in

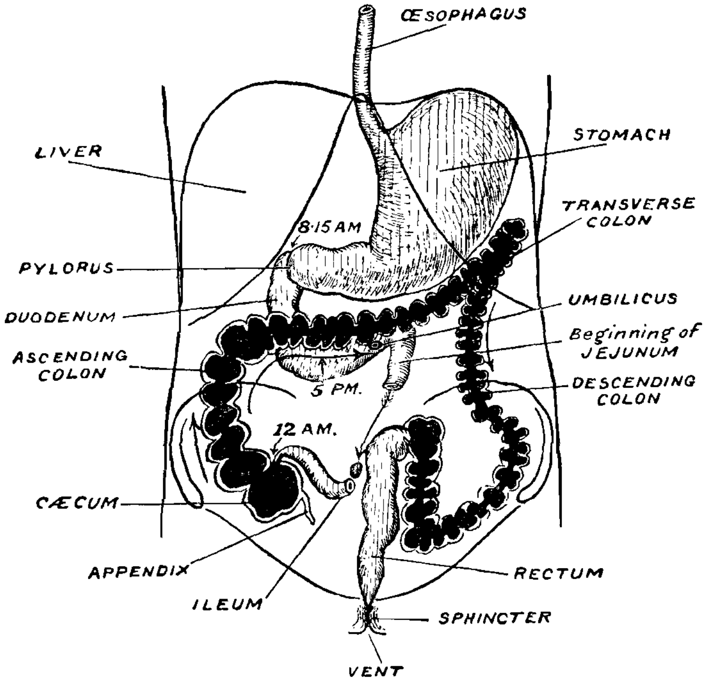


FIG. 43.—Shadow of the great bowel twenty-four hours after a bismuth breakfast. The hours indicate the advance of the meal along the bowel. (After Hurst.)

the final stage of their treatment, they are purposely delayed. Clearly a method of treatment of quite another kind is applied to them in the great bowel.

We examine our friend from time to time during his breakfast. The shadow outlines of his great bowel alter so slowly that we can detect the changes which take place only by comparing the picture of one phase with another taken five minutes later. But if we place our ear over

the seat of the cæcum we discover from the sounds which begin soon after the meal was commenced, that a liveliness has sprung up in the cæcal region. No sooner does the stomach begin to work than signals are issued to the lower laboratories warning them to prepare for the reception of further consignments. The exact nature of the signals or messages thus sent out we have not yet discovered ; but they are probably missives which the active stomach posts in the blood circulation, and which quickly reach their proper addresses in the lower segments of the alimentary tract. The signalmen in charge of one section of the alimentary line thus notify their colleagues in charge of other sections to prepare for further traffic. Nature has done her best to organise the alimentary traffic on a self-adjusting basis.

Although at usual times no movement is apparent in the contents of the great bowel, yet at meal-times, particularly during and after breakfast, a sweeping movement of a peculiar kind can be seen—"mass-movements," Dr A. E. Barclay has named them. Suddenly the beaded shadows of the transverse part of the great bowel—the transverse colon—are drawn together and are shot as a long quickly-moving bolt, which descends the left loin and groin towards the pelvis, where it becomes stationary. By movements of this kind the great bowel prepares for the reception of a new load.

It is a remarkable and, we think, an important circumstance that the first part of the great bowel—the cæcum and ascending colon—are not involved in the clearing operations known as mass-movements. Should we examine our friend forty-eight or seventy-two hours later we shall still find some trace of a bismuth shadow in his cæcum. One may well suspect that the cæcum is charged with a batch leavened by some particular ferment or yeast which has to be husbanded. In this connection we may also note that wind or gas is always present in the cæcum ; no matter when we may tap with a finger the region of the belly in which it lies, we always elicit a drum-like sound.

Having dismissed our bismuth friend for good, we now set out to ascertain the nature of the chemical operations carried on in the great bowel and the particular kind of body-fuel which is there manufactured. Something is known about these matters, but much remains to be discovered. We have seen that it is merely the "tailings" of the food which enter the cæcum by the ileo-cæcal orifice. The refuse shot from the tailrace of the gold-mine, although all the pure gold has been successfully removed from it, may yet contain gold in chemical combination which can be extracted only by the application of special chemical means. That was a discovery which gold-miners made; the refuse heaps of old workings suddenly became of value. At an early point in the evolution of vertebrate animals, a discovery of a similar kind was lighted on. The tailings of the small bowel, after running the long gauntlet of the small bowel, still retained certain valuable materials which could not be reduced and extracted by ordinary digestive juices. Such juices could remove almost the whole of the useful fuels contained in all kinds of flesh food in an animal's diet; but in fruit, roots, vegetables, and particularly in the husks of grains, there was a large food element—particularly cellulose—which passed without being acted on by ordinary digestive juices. Cellulose husks have to be dissolved before the valuable kernels they enclose can be extracted and absorbed. These husks, even straw, hay, and wood, disappear if left exposed to the weather. They are digested and dissolved by bacteria and their solutions washed away by rain. Bacteria, then, were the means which Nature selected for dealing with the tailings from the bowel; they are often given easy access to the alimentary canals of animals by being carried in with the food eaten. The hinder part of the bowel became altered in construction and established as a special laboratory in which the digestive operations might be carried on by bacteria. That is how the great bowel came to be established. The new method was cheap and effective. The production of digestive juices is costly;

their manufacture is a constant drain on the resources of the animal machine. Bacteria, on the other hand, are content to perform the work of digestion for a small percentage of the gains which accrue from their labours. How profitable this novel bacterial method of digestion has proved may be judged from the success of the animal forms which adopted it; the three higher forms of vertebrate animals—reptiles, birds, and mammals—have installed it as a regular part of their alimentary systems. The new system, however, had certain disadvantages. So long as only harmless cellulose-loving bacteria gained access to the new laboratory all went well, but others of a harmful kind could also gain admittance, and hence an elaborate police system had to be established and maintained in the lower bowel to save the body from invasion. Putrefaction also is apt to occur in the stagnant contents of the bowel, leading to the formation of substances which may be absorbed and thus injure or poison the body.

Unless we interpret the operations carried on in the great bowel in the manner just outlined, the changes which we see taking place in it have no meaning for us. We are at a loss, otherwise, to explain the peculiar construction of the cæcum and colon. But when we regard the great bowel as a chamber in which the refuse from our food is submitted to a new kind of digestion we find a key to its apparent mysteries. We then understand why the ileo-cæcal orifice—the threshold between the first and second intestinal laboratories—is guarded and regulated by a sphincter mechanism (fig. 44B). The ileo-cæcal orifice marks the end of one digestive system and the beginning of another. We explain the presence of the cæcum by looking upon it as the stomach of the great bowel. We have seen that it is always partly filled with gas, and that it retains part of one batch apparently to serve as leaven for the next, appearances which suggest a bacterial function. We see, too, why alimentary matter is retained so long in the great bowel; a fermentative change is necessarily a slow one. There are the same two muscular

strata in the cæcum and colon as in the wall of the small bowel, but they are arranged differently. The outer coat is gathered into three bands which run along the colon and pucker the fibres of the deeper lying circular stratum into folds and pouches. That is because the movements and transport system of the great bowel are profoundly different from those of the small. Here there are no peristaltic or "milking" waves. The lower part of the

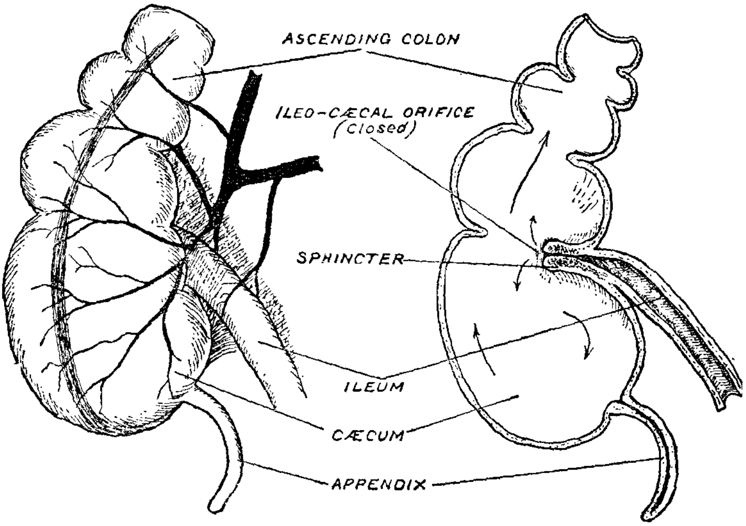


FIG. 44A.—The cæcum covered by its outer or peritoneal coat.

FIG. 44B.—The cæcum, appendix, and ileo-cæcal orifice laid open.

small bowel fills the cæcum in much the same way as the œsophagus forces boluses of food into the stomach. The cæcum, and the same is true of the rest of the colon, has a rhythmical contraction which gently and slowly kneads the material within and is thus constantly bringing its lining membrane into contact with fresh surfaces of its contents. In order that the contents may be thoroughly searched for every particle of digested food, the wall of the colon is thrown into pouches and folds which are ever changing their position and form, and thus coming in contact with fresh material. One part of the great

bowel still remains a mystery—the part which is most liable to become the seat of an acute disorder. This is the appendix. It is shaped like a narrow test-tube and is usually about four inches in length, and about a quarter of an inch in diameter. Its blind end is free pointing towards the pelvis; its mouth opens on the interior of the cæcum (fig. 44B). Its muscular coats are strong and contraction waves sweep slowly along them. It beats with a slow rhythm. It receives material from the cæcum which it works upon, but what digestive changes it effects or what rôle it plays is not known. This highly specialised structure has often to be removed by the surgeon on account of disease and the human machine appears to manage perfectly well without it. This does not mean that it is a useless or vestigial structure. We may lose an eye; to our friends we seem to get along just as well as before. The sufferer, however, knows that such is not really the case; careful observation shows him that there are many things he cannot make out so well as when he had both his eyes. All that we can safely say about the appendix is that it is better to be without one than to possess one which is diseased and therefore liable to cause death. But that it should be so frequently invaded by disease-producing germs will be understood when we look more closely at the nature of the digestive processes carried out in the cæcum.[1]

The reader must not think that the part of the human machine we are now dealing with is one of minor importance—a mere economical contrivance which Nature has fitted to the human machine in order that the products which escape from the small bowel may be salved. The great bowel is one of the largest laboratories in the human body. When laid open and spread out it forms a long narrow sheet, the width diminishing as it passes from the cæcal to the anal extremity. In an adult man the average width of the sheet is about 6 inches, its average length about 70 inches. Its lining membrane therefore exposes a surface for the absorption of food products of about 420 square inches. This, although

[1] See Appendix K, p. 317.

little more than one-fourth of the surface which the small bowel presents to its contents, is still a very considerable area. There are none of the contrivances for increasing the absorbing surface—duplications of the lining membrane, upgrowths in the form of villi—such as we saw in the small bowel. The surface of the lining membrane is covered by the usual kind of paving—mucus-forming units, even more active in maintaining a lubricating covering than in the small bowel. The lining membrane is set with minute test-tube glands. These also throw their products, which, so far as we know at present, are mainly of a lubricating kind, on the surface of the membrane. Under the paving epithelium and between the test-tube glands is a capillary field not so richly fed by arteries and drained by veins as in the small bowel, but yet of an extent that convinces us an important work is carried on in the lining of the great bowel. The paving epithelial units are the active agents in extracting the available products set free in the alimentary contents of the great bowel; they pass the fruits of their labours on to the neighbouring capillary field. From there the products are carried to the liver to undergo further treatment before being issued in the daily ration of tissue-fuel. We know that absorption proceeds most actively in the first part of the great bowel. When the chyme enters the cæcum it is fluid; by the time it reaches the transverse colon it has become reduced to a paste, and in that condition it remains throughout the remaining stages of its journey.

It is manifest that the pavement of the great bowel is a living barrier or screen interposed between a mass of matter seething with bacterial products, good and bad, and a film of moving blood—the blood contained in the capillary field of the lining membrane. The living pavement units have to serve not only as a frontier guard but also as a customs barrier at which all the traffic which enters the kingdom of the body is submitted to scrutiny and accepted or rejected according to the nature of its mission. Clearly our health depends on how the customs

officials do their work, and they will do that according to the nature of the task we throw upon them.

The frontier guard of the great bowel has at its call an ample service of police and sanitary officials. Behind or below the epithelial defence, in the spaces between the miniature test-tubes of the lining membrane, is mobilised a great army of microscopic movable units which serve as police and also as scavengers. All along the lining membrane of the great bowel are scattered minute stations —lymphoid follicles, little larger than a pin's head—which serve as special stations for the intestinal police service. In the lower part of the small bowel and in the cæcum and appendix these stations are particularly abundant, often closely crowded together in the form of extensive establishments. Our health depends also on the administration of police and scavenger services. Services of such kinds must be efficient if a human machine is to work smoothly.

Up to this point we have written as if all the intestinal traffic was in one direction—passing from the alimentary contents to the capillary field of the lining membrane. In the lung we saw that a traffic took place in both directions: oxygen entered the blood, carbon dioxide left it. There is also an export traffic — an excretion — across the lining units of the great bowel. We have seen that its interior is studded with hundreds of thousands of minute test-tube glands. They are always busy—always throwing out a secretion manufactured from the blood circulating in the adjacent capillary field. The excretion lubricates the surface of the bowel, but Nature would never have established so extensive and elaborate a series of retorts merely for the purpose of lubrication. Some secret process of excretion forms one of the essential functions of the great bowel, the exact nature of which we do not yet know.

There is another series of operations carried on by the lining membrane of the great bowel to which the attention of every one is drawn from time to time. The fermentative nature of the digestion carried on in the great bowel must be attended by a free formation of

many kinds of gases. We have noticed that the cæcum is always more or less distended with a gas; a steady volume or cap of air is also maintained in the fundus of the stomach, thus furnishing the left dome of the diaphragm with a cushion of air against which it may work. How are the quantities of air or gas in the cæcum and stomach maintained at a constant level when we are in a state of health? Undoubtedly the amounts are regulated by the activity of the epithelium which lines these chambers. The gases formed during normal digestion in the great bowel are absorbed and transformed by the living units of its pavement. If the pavement units are temporarily damaged, or if the production of gas is excessive from the nature of the alimentary contents or exacerbation of the activity of the ferment-causing organisms, then gas does collect and the bowel becomes uncomfortably distended. One result of distension is to disturb the transport system of the bowel; the engine spindles in its muscular coats are excited to activity, but find their mechanism ineffective for the transport of gaseous contents. Their efforts are attended by a form of pain with which most human beings become familiar at one time or other, particularly after indiscretions of diet.

We have just seen that the great bowel is an elaborately fitted workshop; Nature has spent her most ingenious efforts in its construction. How is it, then, that in recent days the cry has arisen that, so far as man is concerned, the great bowel is a death-trap and that the human race would gain if they lost it? It is certainly true that it brings misery into the lives of millions of living men and women, and that its derangement is the cause of death in thousands. Metchnikoff and those who share his beliefs throw the blame of these disasters on Nature.[1] Are we quite certain that the fault does not lie with man himself? Let us look at how man fared in a period which, in the geologist's reckoning, is not a remote one. He depended for his sustenance on the natural products of the wood, moorland, river, sea, and shore. In summer and autumn he had plenty; in winter

he had to wring a livelihood from roots, husks, shell-fish, and such game as he could capture. Then came man's greatest discovery—the use and management of fire. Food materials which previously had to be ground by jaws and teeth and submitted to the operations carried on in the great bowel before they yielded their quota of body fuels, could now be prepared in a more easily assimilated form by cooking. Then came another major discovery—the provision of a steady and plentiful supply of food by the cultivation of plants and the domestication of animals. Cellulose, which was formerly digested by man himself, was turned into beef and mutton by living factories which were kept in byres and fields. Instead of struggling for a livelihood from the chance products of the field, man suddenly came to live in a world of plenty. Waste of heat from the body was saved by the wearing of clothes and the building of houses. The use of the quern and of the mill saved the time and labour needed for mastication. Then in recent centuries man entered another stage in his rapid progress, one in which the food products of the world came to be emptied on the lap of civilisation. He directed his efforts to obtain the most concentrated and assimilable forms of food possible and succeeded. Every means became employed for cooking and preparing food to pamper and excite a jaded appetite, one often beyond the natural needs of the body. The human machine has thus come to be supplied with a form of fuel for which its alimentary equipment was never designed. Nature spent millions of years in fitting out a laboratory to deal successfully with the natural refuse of the small bowel; and now under modern conditions of diet, we call upon it to perform duties for which it was never intended. When it breaks down from disuse or from having to deal with refuse of a new kind, is it surprising that Nature levies her fines? What, then, is to be done—return to the life of savages? By no means! A driver humours his engine by supplying it with the kind and the amount of fuel it is designed to burn. The human machine is designed for a mixed diet of a kind which modern conditions of

life bring within the reach of most people. Everyone, by a little observation, can find out the quality and quantity which best suits the working of his own machine. Vegetables, fruit, and cereals will at all times provide sufficient work to keep the big bowel in good order.

Our greatest difficulty will always lie in the control and management of the transport system of the great bowel. Every year fortunes are made from the sale of drugs which are supposed to give—and can actually give—a filip to its transport system. We have seen that the great bowel has its own pulsatile rhythm and its own "mass-movements." They are regulated by an elaborate network of nerve fibres and nerve cells placed between the two strata of the muscular coat. The nervous network is linked up with certain exchange centres in the spinal cord. Through those centres the movements of the great bowel may be influenced by events occurring in other and even distant parts of the body. Unfortunately the nervous network in the wall of the bowel is exposed to certain products of absorption or of inflammation and may be thus damaged. No doubt its action may also be affected by substances contained in modern beverages—such as the essential condiments of tea and coffee. It is also true that the nervous mechanism is accessible to certain drugs which can stimulate it to action, but unfortunately an artificial stimulus sooner or later comes to replace the natural one and then its assistance becomes a necessity. No drug can supply the place of the natural stimulus.

For the final discharge of the alimentary contents a simple kind of "touch-button" mechanism is employed. The act is controlled by an exchange centre established in the lower part of the spinal cord. When the rectum—the final chamber of the intestinal tube—has become loaded by the discharge of a "mass-movement," a "call of nature" arises. When the contents of the rectum are forced downwards by a voluntary effort to the vent, certain transmitting stations placed there are touched, messages are automatically dispatched to the controlling

centre in the spinal cord, the sphincter which guards the vent is relaxed, while the muscular coat of the rectum is thrown into an expelling contraction. The act is started by an effort of will, but it is conducted and completed by an automatic mechanism. If the machinery breaks down, the fault is most likely to lie in that part which is under the control of the will. If we neglect the signal of uneasiness, if we contract irregular habits, then the rectum ceases to be sensitive to loading and therefore fails to issue warning messages.

There is also a minor matter which requires mention before this chapter is closed—one which is linked up with the condition of the human alimentary system. Philosophers love to speculate as to what man is likely to become under our ever-growing civilisation. They picture him in the future as a great brain wrapped in a body from which the grosser animal qualities have been moulted. They think of him as living on a concentrated nectar diet, one which will supply his body with a body-fuel already prepared for use. Man is to become, so it is said, an ethereal creature which will live, burn, and grow a brain fit to sound the utmost recesses and secrets of the universe. Great and kind thoughts are certainly worth living for ; thinking can certainly comfort the evening of life. But he who believes he can make man happier by feeding him on nectar and reducing his alimentary tract to the condition of the feed-pipe of a motor cycle is doomed to a disillusion, for the greatest zests of life are centred round the supply of our daily wants—wants created by a robust digestive system. A nectar-consuming ethereal mortal will never be a match in any circumstance of life for the man or woman who is blessed with a sound alimentary outfit, such as we have inherited or should have inherited from long-past ancestors.

CHAPTER XXI

A POSTAL SYSTEM OF A PECULIAR KIND

In previous chapters we have examined the contrivances which have been fitted within the human machine for the preparation of the fuel it consumes. In this chapter we begin the consideration of another system of structures altogether, one which is needed to link up the various parts of the machine so that they will move at the right time, in the right order, and at the right rate. Without a co-ordinating or timing system a machine cannot be made to perform efficient work. The engine of a motor cycle is provided with a co-ordinating or timing system. The engine cannot run unless certain events take place in a certain order and at a certain time and rate. The inlet valve must open at the beginning of the first or suction stroke and close at its end ; the combustion mixture must be fired when the second or compression stroke is completed ; the outlet valve must open as the fourth or exhaust stroke sets in and must become promptly shut when that stroke is finished. The engineer has co-ordinated these events by means of a timing gear—a system of toothed wheels driven from the crank-shaft. On one side of these revolving wheels are set movable fingers or cams, so placed that they open and shut the valves and break the electric current to the sparking-plug at the instant of time which is found to be most effective for the working of the engine. The co-ordinating or timing system of a motor cycle, then, consists of a series of revolving toothed wheels set so as to be turned by the crank-shaft at fixed rates.

In the human body the time gearing is so different from that of a motor cycle that, if we are to make its nature clear, we must study it in a machine, not made of metal, but made of men—an army. An army is a fighting moving machine composed of hundreds of thousands or millions of living units. We have seen that the human machine is made up of countless millions of living units—the individual soldiers of our bodies. An army, like the human body, is made up of several systems or departments. The fighting units are formed into army corps, divisions, brigades, battalions, companies, and platoons. An army has its service corps or alimentary system, its transport and its intelligence services. The brain of the army is placed in a controlling centre—General Headquarters. That centre has to be linked up with all departments so that the work done by each may be timed and co-ordinated to serve a common purpose. The staff at general headquarters has many contrivances at its disposal for issuing orders to and of obtaining information from the various departments spread out between the firing-line and the base. It may use the ancient and primitive method of dispatching orders by messengers, or, if time is not pressing, send them through the army postal system. If orders are urgent, then a totally different contrivance is employed ; they are dispatched over the wires or nerves which link general headquarters to every part of the fighting machine. The activities of millions of soldiers are thus co-ordinated by the employment of various systems of communication. It is also manifest that neighbouring army corps, divisions, brigades, battalions, and companies must be kept in touch with each other's movements. They cannot trouble higher quarters with each disposition which has to be made to keep the firing-line intact. There must be intercommunication independent of headquarters. Each soldier, although acting under strict orders, still retains individuality of action. He may communicate with and influence the men who are fighting side by side with him. There is also direct communication between the units in

the ranks. Thus millions of men are knit together to act as a single machine by the employment of various systems of communication, some of which act slowly, others almost instantaneously. We are to see that the units of the human machine are also linked together by a dual system—a postal and a telegraphic.

That the human body was provided with a quick-acting or telegraphic system, medical men have known for hundreds of years. From its brain and spinal cord—the G.H.Q. of the human machine—they could see great cables of nerves issuing in all directions, linking the various members to the controlling centres. They knew that messages sped along the wires of the nerve cables, carrying orders and information from and to the commander-in-chief and the various departments of his staff. It is surprising to think that it is only in quite recent years that we began to suspect that the human body was also provided with a postal system. Our previous blindness was all the more remarkable because we knew that great colonies of simple units, such as make up living corals and sponges, did communicate with and control each other, and yet, as was well known, these colonies were unprovided with nerve systems. We were also aware that among primitive peoples, like the aborigines of Australia, there was neither postal nor telegraphic systems; one tribe communicated with another by sending out a messenger carrying a stick on which certain symbols were rudely carved. We ought to have suspected that, in the evolution of the human body, a postal system would precede a telegraphic one. That was not so, however. The first clear recognition that the human body possessed a postal as well as a telegraphic system was made by Professor Starling in 1904. The circumstances under which his discovery was made were mentioned in a former chapter while describing the mechanism which sets the pancreas in action (p. 199). The late Sir William Bayliss and he found that the pancreas began to form and pour out its digestive juice upon the receipt of certain missives which were posted

by the living units lining the upper part of the duodenum. The arrival in the duodenum of the acid contents of the stomach caused the dispatch of secretin, the substance or hormone which acts as a missive for stimulating the pancreas to action. Secretin is posted in the nearest letter-boxes or capillaries in the duodenal wall and is carried away in the general blood circulation, which serves for all kinds of postal traffic. In a postal system where there are no sorters and which must be conducted by an automatic mechanism, letters or missives cannot be addressed in the usual way. Their destination is indicated not by their inscription but by their shape. The molecules of secretin may be regarded as ultramicroscopic Yale keys sent out to search for the locks of letter-boxes which they can fit and enter. They fit and can enter only the letter-boxes of the pancreatic molecules, and hence they must circulate round the body until they automatically find their destination. What is still more wonderful in this system is that the letter-boxes, or we may call them locks, have a positive attraction for the key-missives which are destined for them.

To such key-missives as are posted in and delivered by the general circulation, Professor Starling gave the name of *hormones*. The muscular engines of the body use the carbon dioxide which they cast into the circulation as a hormone or missive to inform the respiratory centre in the medulla of their needs and to stimulate it to action. The harder the muscles work the more is their need for oxygen and the greater is the quantity of carbon dioxide which has to be got rid of; the respiratory bellows must meet their requirements by ventilating the lungs more rapidly. The more the carbon dioxide accumulates in the circulation, the more acid becomes the reaction of the blood; and the more the blood becomes acid in reaction, the greater becomes its power to stimulate the respiratory centre. In this instance the carbon dioxide missives deliver their message while on their way to a final destination—the lungs. As our knowledge increases we see that a postal system is extensively used

in the control or management of the human body. Several instances have been alluded to in former chapters.

The most remarkable advance of recent years was the discovery that there are certain laboratories or glands in the body which are entirely devoted to the manufacture and dispatch of these key-missives. These laboratories are usually called glands of internal secretion, but such a name gives no indication of the important control they exercise on the growth and working of the human machine. These glands, laboratories, or control offices are placed in various parts of the body and all are of small size. Two of them, the right and left adrenal glands, each of the size of a segment of a small orange, are placed over the right and left kidney. They receive an abundant supply of blood and also a leash of nerves which places them in telegraphic communication with nerve exchange centres in the spinal cord. The largest of the series, the thyroid gland, is placed in the front of the neck, astride the wind-pipe and just above the breast bone. It, too, has a nerve supply from the involuntary system as well as a rich blood supply. Then, within the head, cradled in the floor of the skull and attached to the brain by a stalk, is the pituitary gland about the size of a ripe cherry. There is also a minute one, little larger than a barley-grain, the pineal gland, buried deeply between the lobes of the brain. Lastly, in the genital glands, besides the main parts which have to do with the formation of human seed, there is a second element which is concerned in the production and issue of controlling missives. So small is the total mass, that if all the glands of internal secretion were rolled together they would form a parcel small enough to go in a waistcoat pocket, yet such a small mass can influence the working and growth of the whole body.

In each of these small but busy laboratories, hormones or missives of two kinds are prepared. There are those which are made up and dispatched for immediate use in controlling or tuning parts of the body concerned in the performance of definite movements or operations. Then there is a second class which, although posted daily, yet

do not make their effect evident immediately because they have merely to do with the growth of parts—parts which are combined together when carrying out a common action. The missives sent out by the glands of internal secretion, then, are of two kinds—functional and developmental. The microscopic units of every organ of the body, be it a muscular engine or a laboratory for the preparation of a digestive juice, have always a double duty. They have not only to contract or secrete; they have also to take a share in the development, growth, upbuilding, and maintenance of the engine or laboratory of which they form a part. Hence every unit should receive two classes of hormones: one to tune them for their share in the active work of the body, and the other to sensitise and regulate them in what may be called their household duties.

We should be led too far afield were we to follow out the multiple activities carried on in the hormone factories. We shall confine ourselves to one example from the adrenal factory to illustrate the use served by hormones in regulating a functional act and two others, one from the pituitary gland and another from the genital glands, to show how they control the *functional growth* of the body. Professor W. B. Cannon of Harvard University was the first to piece together the evidence we are now to examine relating to the manner in which the adrenal missives mobilise the systems of the body when a great physical effort has to be made. When our brain perceives that a great effort is required of us to overcome a difficulty or perhaps to avoid a danger which is imminent, it immediately braces up all the muscular engines under its control. At the same moment as the brain's commands are dispatched to the muscles, messages are automatically sent out from nerve centres in communication with the adrenal bodies—telegraphic messages. The result is that the adrenals at once begin to dispatch with alacrity a hormone—adrenalin—by the usual postal system—the blood circulation. The action of adrenalin upon the stopcock mechanism of the body is instantaneous; those

supplying the alimentary tract are closed to a minimum, but those of the muscles of the heart and lungs and of the nerve centres immediately concerned in the effort are opened to their widest. There is a nerve system—the vasomotor system—for controlling the stopcock mechanism of the arterial system, but adrenalin comes into play and relieves or assists the system in tiding over a prolonged effort. Adrenalin has also another effect. When muscles are working hard they consume fuel quickly and need an increased as well as a steady supply. That, too, is provided by the adrenal hormone. As it circulates through the liver it stimulates the sugar-producing laboratories of that great gland to set its stores free in the blood. By means of the circulation these stores are carried to the muscular engines, thus furnishing them with an ample and steady supply of fuel.[1] At the same time as the adrenal laboratories begin work, nerve messages reach the thyroid gland in the neck, which also passes into a state of activity. The thyroid hormone thus thrown into the circulation has the same effect on the tissues of the body as the impregnation of paper with a nitrate solution. The addition of nitrates makes a paper scintillate and smoulder rapidly, as in match paper. This is the effect which one of the thyroid hormones has on the living tissues of the body ; it sensitises them and makes them greedy for oxygen ; it thus aids in combustion and in the performance of work. It reinforces and increases the action of adrenalin. Dr George Crile has shown that both of them, particularly the hormone of the adrenal bodies, stimulate the nerve corpuscles of the brain to their full activity. There is no postal mechanism corresponding to the hormone system in the organisation of a modern army. A general order which confers special rations on the men in the firing line, with extra allowances of rum, tobacco, and coffee, would represent a poor substitute for the stimulating and controlling messages sent out to the body by the adrenal and thyroid glands.

We now pass on to consider the effect of one of the developmental or growth-regulating hormones which is

[1] See Appendix L, p. 321.

manufactured and posted in the general circulation by the small pituitary gland attached to the base of the brain. We became aware of its peculiar action quite unexpectedly. In 1886, Dr Pierre Marie of Paris, while still a young medical man, was consulted by two women who complained of headache and mentioned incidentally that they had become so changed in appearance in recent years that even those to whom they ought to be best known could scarcely recognise them. Their faces, particularly their jaws and noses, had become enormous ; their hands and feet had become thick, clumsy, and overgrown, as if they had been intended for the limbs of huge labouring men. Dr Marie named the disorder or disease Acromegaly. Very soon after he published an account of these two cases, and thus drew attention to the condition, many instances were seen and investigated by medical men in Europe and America. The disease proved to be quite common, although it was never noticed until Dr Marie sensitised our eyesight. Very soon it was discovered that every one in whom this disorder was well marked had a pituitary gland which was irregularly overgrown ; it was during the period of its overgrowth that the configuration of the patient's body underwent the remarkable changes just mentioned. Then a further discovery was made. It was found that those men and women who on approaching their twentieth year suddenly shoot up into giants or giantesses—men or women over seven feet in height—were also the subjects of a riotous overgrowth of the pituitary gland. Giantism and acromegaly are closely related conditions. Almost all giants are not only tall but also suffer from acromegaly. In this way light was thrown on an unknown and unsuspected growth-regulating mechanism of the body. It is only now becoming apparent what the true nature of this mechanism is. We all knew that the blacksmith's biceps becomes a big and strong muscle. We thought that a sufficient explanation of that fact was merely to say that overwork gave rise to overgrowth. This kind of answer serves to cloak our ignorance. The real question we

have to answer is : How does overwork cause a muscle to grow big and strong ? You may wear an engine out by hard work, but you cannot make it stronger by such means. Somehow, in a manner we do not yet understand, the brain, when it is about to set muscles into motion, can make a demand on the pituitary gland. It can unlock the flood-gates of the pituitary and set free its hormones which, circulating in the blood, sensitise the living units which are concerned in the upbuilding and growth of muscles, so that they respond to work by becoming larger. If the pituitary hormone is thrown out too abundantly, as in giants and in the acromegalic, the muscles are over-sensitised and respond too readily, even when worked to a slight degree. If the muscles are increased in power then the levers on which they work must also be strengthened ; the bone-builders have to be sensitised at the same time as the muscles if a useful effect is to be obtained. It is also necessary that other systems of the body be strengthened. A great muscular system needs a great heart or pump to feed it and great lungs and respiratory bellows to supply it with an adequate amount of oxygen. The alimentary system has to be increased to supply the machine with sufficient fuel. These changes are exactly what we find overtaking the human body in the first outburst of acromegaly and giantism. The heart and arteries become hypertrophied ; the chest becomes enormous, the jaws, the muscles of mastication, markedly overgrown ; the muscles at first develop great strength, then sink into impotency ; all the bones, particularly the areas giving attachment to muscles, become thick, clumsy, and their muscular attachments exaggerated. Soon they too begin to atrophy. Clearly, then, one of the harmones posted in the general circulation of the blood by the pituitary gland has to do with the sensitising of all the systems of the body concerned in muscular work. The growth hormone of the pituitary gives to the systems of the body the power to respond to the burdens which are cast on them. There is no mechanism of this description in the organisation of any

kind of machine—except in that kind which is made by Nature.

Long ago men discovered that the sex glands had a powerful influence on the growth of the body. They were well aware that the nature of both body and mind became altered if the genital glands were removed in youth. The whole build of body becomes more slender in the castrated; muscles are less robustly developed; the bones of the limbs grow longer, but are less powerful; the beard fails to sprout; the larynx undergoes no transformation as adult years are reached; the sexual system retains a boyish development; there is a marked tendency for fat to gather on certain parts of the body; the mental outlook and the resolution for action are completely altered. In the eunuch we seem to be dealing with a new species of mankind. All these facts were known long ago, but it was not until we had grasped the idea that the growth of the body is regulated by hormones that we understood how castration brought about such remarkable changes in the body. John Hunter knew that the state of the genital glands regulated the development and growth of the sexual system. By transplanting the genital glands, and also parts of the body which he knew formed part of the sexual outfit—such as the spurs on the legs of fowls—he observed that definite alterations could be effected by altering the nature of the sexual glands. But it was not until we came to know of growth-regulating substances that we clearly perceived in the genital glands a double function. They are not only seed treasuries, but also busy offices from which missives are being constantly dispatched to the adrenals, thyroid, pituitary, and other growth-controlling laboratories. Certain changes are effected through the adrenal glands. In their cortex there is a laboratory for the manufacture of hormones which stimulate the appearance of sexual characters. Occasionally a child, scarce off its mother's lap, begins to assume, as a monstrous garb, the face, voice, and demeanour of sexual maturity. Such a manifestation is always accompanied

by a profuse overgrowth of the rind of the adrenal glands. In these glands are manufactured missives which have to do with the growth of sex characters. Professor Bulloch and Dr Sequeira were the first to perceive the relationship between a manifestation of sexual precocity and a pathological overgrowth of the adrenal bodies. The sexual glands also use the pituitary laboratory in effecting the display of secondary sexual characters. Even in the regulation of the size of our bodies, the quality of our minds, and the cast of our countenances Nature has designed and set in motion a wonderfully organised machinery.

Mention was made, when surveying the third great chemical laboratory of the alimentary tract (Chapter XX., p. 215), of the immense and movable armies of microscopic corpuscles which could be mobilised for police or sanitary duties. So far, however, we have given no indication to the reader of the busy traffic carried on by white corpuscles. They swarm in the blood stream as it circulates round the body. There are various kinds of them, and we shall learn the nature of their duties as our modern investigations proceed and fructify. But it is extremely probable that one variety of them, if not more, are really errand-boys on their way to deliver messages or parcels, and that the gland masses which are built up in and round lymph channels serve both as nurseries for the upbringing of such messengers and also as offices from which they are dispatched on their errands.

In this chapter we seem to have gone a long way from the simple idea with which we set out—a comparison of the human machine to a motor cycle. Our comparison held very well, and was instructive, so long as we looked on the human body as a moving machine furnished with muscular engines, levers, pumps, and bellows. It was when we came to deal with the laboratories in which the fuel for the machine is prepared that a strict comparison between the body and a machine of metal became more difficult to uphold. When we looked beneath the surface of the alimentary laboratories we discovered that their

constitution and also that of the human machine are altogether different from the machines designed by man. Our bodies are made up of billions of microscopic living units, each unit having an independent activity, and yet an activity which has to be co-ordinated with the work done by neighbouring units. The operations carried on by one brigade of units has to be co-ordinated with the activities carried on by brigades in distant parts of the body. To find a parallel to such a condition we have to think in terms of an army and of its elaborate organisation. The human body is built like a machine, but has been given the organisation of an army. How marvellous that organisation is we shall proceed to show in the chapters which follow.[1]

[1] See Appendix M, p. 326.

CHAPTER XXII

THE MASTER CONTRIVANCE OF THE HUMAN MACHINE

THE most wonderful part of a motor cycle is the contrivance by which it is controlled and driven. That contrivance is placed within the head of the man who occupies the driver's seat, and is known as the human brain. A motor cycle, however ingeniously it may be designed and engined, becomes a complete and useful machine only when a human brain is fitted to it. Even a human body, robust, supple, and sound in every way, is occasionally provided with a brain of so poor workmanship that it may be incapable of managing even a motor cycle. The human brain, then, must be regarded as an intrinsic part of all machines driven by men—be they running, flying, or swimming machines. All are controlled by the most marvellous of Nature's contrivances—the brain. It is this machine or contrivance which forms the subject of the present chapter.

The brain itself is a machine—by far the most intricate one of which we have any knowledge. We shall throw some light on the nature of the work it can do, if we consider for a moment what we should require of an engineer were he to undertake to supply us with an automaton driver. In the first place the automaton must be able to balance the motor cycle on the straight road as well as in taking sharp corners. This difficulty could probably be got over by applying the principle of the gyrostat ; we shall find that Nature has discovered a simpler way. Then it would have to be fitted with a pair of minute photographic cameras or eyes, set so that they could converge for near

vision and swing into parallel lines for distant objects; the lenses must have a self-adjusting focussing mechanism. On the back of the optic cameras sensitised films would have to be fitted, capable of being continually renewed and of registering the continuous series of pictures presented as the cycle spins its way along streets and roads. Cables of wires (to serve as optic nerves) would be required to carry away the chemical records formed by the landscape pictures as they fell on the sensitised film of the camera to a record office or brain. The machinery fitted as a brain must be able to interpret the chemical records which the optic wires carry to it from the camera and pack them away in such an orderly manner that they can be recalled at the demand of the automaton's will. This is merely the receiving machinery required in the brain. Suppose an approaching vehicle comes within the pictures focussed by the optic cameras, then its size, shape, speed, and position have to be estimated by the recording mechanism in the fraction of a second. For this end the brain of the automaton must be fitted with machinery for comparing and estimating the impressions which are reaching the registering machinery. This estimating machinery must be one already stored with past pictures of moving vehicles of all kinds—pictures which must be summoned in an instant and compared with the picture of the approaching danger now signalled from the registering part of the brain. The registering and estimating mechanisms belong to the intelligence department of the brain; they are powerless unless they can command an executive service. Hence a third or executive mechanism has to be added to the automaton brain—one which can judge the exact degree to which the handle bars must be turned to avoid the approaching vehicle. The handle bars, we shall suppose, are worked by means of reciprocating engines in place of hands and arms. The executive mechanism of the automaton must be connected with the engines which control the handle bar by wires or nerves, and over these wires must be able to dispatch messages—electrical, let us suppose—which will start the guiding engines at the right

moment, at the right rate, and stop at the right instant—in short, perform the carefully balanced movements which an accomplished driver carries out almost automatically as he passes a vehicle in a narrow road.

These are merely a fraction of the parts of the mechanism or brain with which an engineer must provide an automaton driver. The movements of the optic cameras must also be automatically regulated. Let us take an illustration. We shall suppose a child runs across the road. Its shadow will suddenly appear in the pictures registered by the camera or eyes of the automaton. The cameras must be switched at once on the child. There is no time to call in the higher machinery of the brain ; a shorter pathway must be used to get access to the machinery controlling the muscles or engines which regulate the movements of the camera, so that the danger may be brought into full focus at once. Nature has provided the eyes of her automaton drivers with such a machinery. Then there are warning sounds which have to be registered, deciphered, and acted on. Receiving, registering, and interpreting of sound waves entail the elaborate machinery of the ear, with communicating cables of nerves and multitudes of exchange or brain centres. Sounds have to be analysed and then compared with memories already stored in the brain machinery of the automaton. The automatic ear must be capable of detecting the slightest change in the sounds emitted by the engine. A contrivance for the detection and interpretation of smells would certainly be useful. The automaton could certainly be made to start or stop the engine at fixed times ; it could be made to regulate the throttle valve according to needs, to change gear and look after the supply of lubricant. But what if a nut worked loose, or the engine became heated, or the connecting-rod broke ? Or suppose the automaton came to cross roads and had to ask its way ? The fitting out of an automaton driver to answer all these needs represents a problem so intricate and difficult that no engineer would even dream of undertaking it. He would regard it as a mad enterprise. Yet

it is an enterprise which Nature has carried to a triumphant issue. The human brain represents Nature's Master Contrivance.

This contrivance which we are now to look at can not only drive machines ; it can invent and create them. It was the machinery of the brain which discovered the uses of fire and of iron ; found out the elements which compose the earth, sun, and stars ; discovered the laws which regulate the movements of planets. Shakespeare's plays were conceived and written by such an instrument. The brain machine has discovered how to bridge space and time ; it balances and determines the fates of armies, fleets, and nations. Nothing is too small and nothing too great to fall within the compass of its machinery. It is such a wonderfully contrived machine that, although the most learned men have dissected and examined it for thousands of years, they have done little more than cross the threshold of its organisation. But every step forward has made them more and more certain that its mechanism can be unravelled and that the only darkness about it is the shadow cast on it by their own ignorance.

The brain, then, is a great administrative, governing machine, simple enough in outward appearance and only imposing because of its bulk. In fig. 45, A, the right half of the head has been removed to expose the greater part of the central nerve machinery—the brain and spinal cord. The brain itself is housed within the cavity of the head—the bony-walled cranial chamber, which varies much in size or capacity. A chamber which could hold between 50 and 52 oz. of water (1430–1480 cubic centimetres) is a common size amongst Englishmen ; in the English woman the chamber, in conformity with her body, is of smaller size—its capacity being in round numbers 12 per cent. less than that of the male. In life the cranial chamber is perfectly filled, the brain itself occupying 93 per cent. of its capacity, while the remaining space is taken up by the coverings or wrapping of the brain, the cerebro-spinal fluid which bathes it inside and out, and the great capillary fields which permeate its coverings and

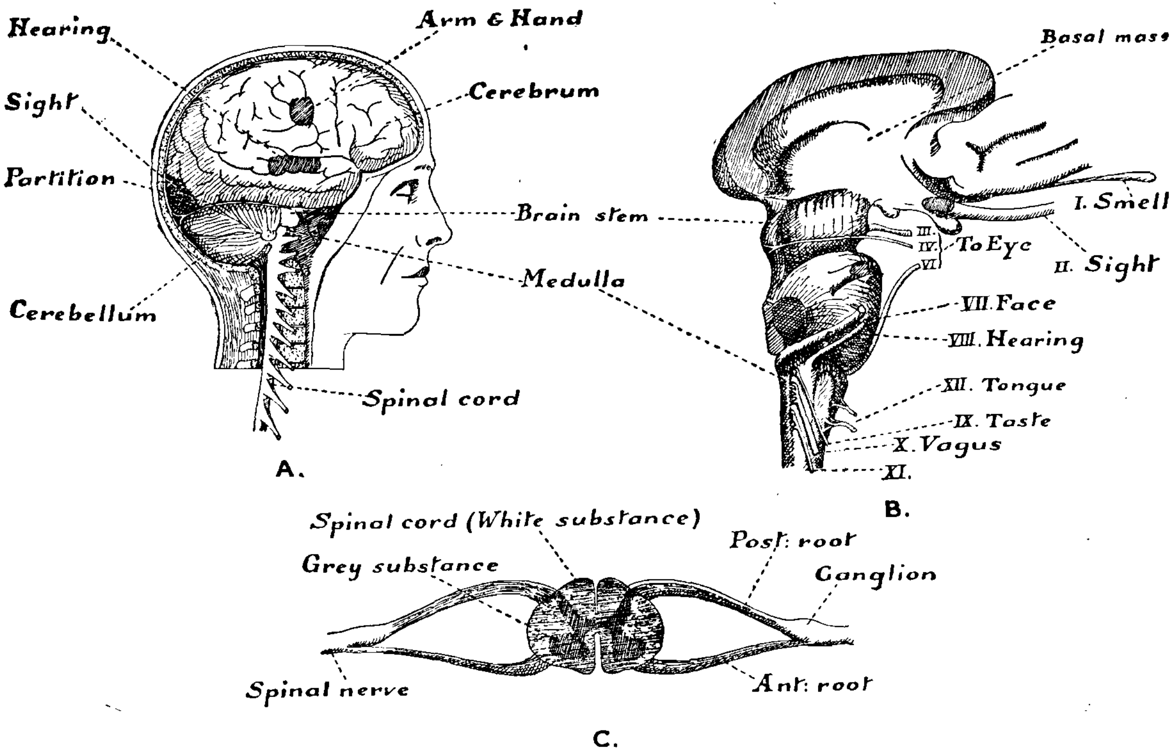


FIG. 45.—A, The brain and spinal cord exposed from the right side. B, The brain stem, showing the origin of the cranial nerves. C, Section across the spinal cord showing the manner in which the spinal nerves arise by two roots.

substance. The capillary fields are freely fed by large arteries and drained by veins into special channels—the venous sinuses. The great machine itself and the pipes laid on to provide it with a constant supply of fuel and oxygen are packed away in the neatest sailor-like fashion. The cranial chamber is divided into a large upper and a small lower storey by a horizontal membranous partition, in which there is an open doorway giving passage to the great brain stem (fig. 45, A). In the upper compartment are lodged the two great cerebral hemispheres, right and left, linked together by a great bridgework of nerve fibres —the corpus callosum. The right hemisphere, we shall find, presides over the left half of the body, and the left one over the right half. It is the left hemisphere, for example, which regulates the movements of the right hand. Then in the smaller and lower storey is housed the cerebellum and also the continuation of the brain stem which issues from the cerebral hemispheres in the upper compartment. The part of the stem which lies in the lower storey, and to which the cerebellum is linked by great nerve cables, is the medulla, or, to give its name in full, the medulla oblongata. In former chapters we have often had occasion to refer to the vital controlling centres lodged within the medulla, centres which regulate the pumping of blood by the heart, ventilation of the lungs, and management of the alimentary laboratories. Through a wide opening—the foramen magnum—in the base of the skull the cranial chamber is prolonged into the spinal chamber, an elongated corridor in which is lodged a continuation of the brain stem—the spinal cord. Thus the great central nerve machine, which we are now examining, extends from the forehead to the lumbar region of the spine—the small of the back.

In the great alimentary laboratories we found that the living microscopic units—each a minute fuel factory—were grouped so as to form a lining for the chambers. In the cerebral hemispheres or cerebrum, and the same is true of the cerebellum, we find Nature has adopted an opposite plan. The microscopic operatives which

manipulate and dispatch nerve messages are grouped so as to form a stratum or layer on the surface of the cerebral hemispheres. When the rind or cortex of the cerebrum is cut into, its substance is seen to be made up of white matter except a very narrow grey band or strip placed just under the surface covering. This band makes up what is called the cortex or cortical matter of the brain. It is the presence of myriads of minute operatives which gives the band its grey colour. The white matter is composed of the microscopic fibres or living wires which carry messages to and from these operatives. These living units in the cortical stratum form the highest class of nerve operatives. When we wake in the morning the sheet of grey cortex on the brain becomes the screen on which is lit up the cinema of the outer world. It lights up and becomes our field of consciousness. The cerebral operatives are thus spread out and form a thin and extensive layer, varying in thickness, in some parts being almost a quarter of an inch in depth, and in others little more than a tenth of an inch. The operatives are spread out on a wide field because of the enormous number of message lines which have to be brought to and from them. Their battalions are closely set, twenty units deep and more, with cable cords piercing their ranks. Nature has increased the extent of the cortical field by throwing the surface of the cerebrum into folds or convolutions. Between the convolutions are depressions or sulci (fig. 45, A). Groups or areas of convolutions are separated from neighbouring groups by deep depressions or fissures. Everywhere, on the convolutions and within the sulci and fissures, extend the grey cortical battalions of nerve operatives or cells.

A few pages back mention was made of the brain mechanism needed for an automaton motor-driver. One requisite was a contrivance for registering the pictures which fell on the sensitised plates of the camera, representing the eyes of the automaton. In fig. 45, A, the situation of the sight-registering mechanism in the human brain is indicated. It is placed far back on the cerebral

hemispheres, near their hinder or occipital poles. The machinery is represented by the cortical areas of the occipital regions. The area on the right hemisphere registers the field of vision which lies to the left side of the middle line of the face ; the left hemisphere, the field of vision to the right of the middle line. Then immediately in front of the registering areas are those for the interpretation or comparison of the messages received by the registering areas. Still further forwards are the administrative areas of cortical operatives, the position of those for the left hand and arm being indicated in fig. 45, A. In the same illustration are indicated the cortical areas which carry on the registration and interpretation of sound waves, areas which are thrown into a state of great activity when we listen to learned lectures. It is by the invention of an elaborately contrived cortical mechanism that Nature has given the human brain the power to see, hear, think, and act ; countless myriads of microscopic operatives carry out the functions of both remembrancer and judge. They constitute the spheres of pure intellectual activities.

The great cortical fields (of the cerebrum) represent the highest flights of Nature's inventive genius. Prof. Elliot Smith has made it very clear to us that the capacity of an animal to learn new movements or acts depends on the extent and quality of the cortical areas. In the brains of anthropoid apes we see the overgrowth of cortical areas which culminates in the enormous development attained in the human brain. Without these cortical fields, as Dr Henry Head has proved in recent years, we should know nothing of time or of space. The nerve centre or grey substance of the cerebrum, however, are not all spread out in its cortex. Deep within the hemispheres, forming swollen enlargements at the root of the brain stem, are two great masses of grey nerve substance. These masses represent the great receiving stations which deal with the continual incoming flood of messages which give us our feeling of comfort or discomfort, of pleasure or pain, messages which make us

laugh or cry ; they are the seat of all emotional disturbances. Likewise in the brain stem itself, in the medulla, and in the spinal cord nerve operatives are grouped in stations or centres which occupy the deeper or inward parts. In the spinal cord, which is imperfectly divided into right and left columns, we find the white matter, made of the cables uniting the operatives of one station with those in a distant station, set on the surface, while the grey matter forms the core of each side column (fig. 45, C). A bridge-work crosses within the spinal cord and unites the grey cores and the enclosing white cables of the opposite sides. The spinal cord, with its central cores of grey matter and outer covering of white matter, represents the original manner in which the central nerve machine was constructed. It was only when Nature came to elaborate the cortical areas of the mammalian brain that she reversed her method and spread the operative units on the surface and placed the communicating cable in the centre. The adoption of this simple modification in construction gave her, as Prof. Elliot Smith has demonstrated, an unlimited field for expanding the cortical areas—a freedom which made the human brain possible. In birds and reptiles Nature pursued her old method, packing their cortical substance in the interior of the hemispheres, with the result that their further growth soon became impossible for lack of space.

We have made a rapid survey of the great central nerve machine. We must now glance at the cables of living wires which place it in communication with every part of the human body. From the spinal cord there emerge thirty-one pairs of nerves (fig. 45) destined for the right and left halves of the body and the limbs attached to these halves. Each nerve issues from the cord in two divisions or roots. On the hinder or posterior root (fig. 45, C) is a swelling or ganglion, packed full of the kind of operative we may name message-transmitters. Each one of them is set upon—forms an intrinsic part of—the nerve fibre or wire through which its messages are carried. The spinal nerve-trunks issue

from the canal of the backbone by special windows placed between the vertebræ. Opposite the arm and the leg these nerve cables are exceptionally large, because the nerve traffic between the limbs and the central nerve machine is a particularly busy one. Five pairs of these spinal nerves enter the upper limbs, while the lower limbs receive seven pairs of the largest size.

Within the skull twelve pairs of cranial nerves arise from the brain stem (fig. 45, B). The first pair go to the nose, the second pair to the eyes ; both of these are directly connected with the cerebrum. The eighth, springing from the medulla, supply the ear ; the ninth contain the fibres which arise in the taste buds of the mouth ; the tenth, or vagus pair, spring from the medulla and descend within the thorax and abdomen, where they bring the lungs, heart, and stomach into communication with the small masses of grey matter in the medullary stations which serve as exchange centres for nerve "calls." The other cranial nerves have to do with the muscles of the eyeball, face, and neck, and with the nerve supply of the skin of the face. Thus each half of the body is linked to the central nerve machine by forty-three nerve cables, varying greatly in size, but all of them issuing in orderly sequence from above downwards. No matter how small the part of the body damaged, it is certain to have nerves and thus have the means of communicating with the brain.

The central nerve machine, then, is constructed of two elements—microscopic living operatives and living wires—more delicate than the finest threads of a spider's web. Both operatives and wires, being alive, must be supplied with fuel and oxygen. They apparently need a plentiful supply, for the carotid arteries which pierce the base of the skull to carry blood to the greater part of the brain are large vessels. They send relatively small branches to supply the deep masses of grey matter, but the cortical areas are permeated with a rich capillary field. The machinery which supports our consciousness needs a liberal blood supply. Two smaller arteries—the ver-

tebral—enter the skull and assist the carotids. The spinal cord is provided with a succession of small arteries. There is one curious feature of the blood circulation in the central nerve machine. Being contained in a chamber with rigid walls, one which is always quite full, every charge of arterial blood which enters the chamber has to displace an equal amount of venous blood. Thus each pump of the heart always fills the arteries and empties the veins of the brain at the same time.

We know that the nerve operatives are particularly sensitive to a lack of oxygen. They die the instant their stock is exhausted, and at the most that stock will not last them ten minutes once the outside supply is cut off. Hence in people who have been submerged in water for ten minutes and apparently drowned, although the heart and lungs still retain life and can be revived, it is usually the case that the nerve operatives or cells are already dead and destroyed beyond recovery. The great need for oxygen, perhaps, accounts for the liberal blood supply to the brain, for we know that the nerve operatives consume, even when they are writing books, a very small amount of fuel. Even the kind of fuel they consume we do not yet know. Their staple diet is not likely to be the rough carbo-hydrate fuel which muscles turn into work. Perhaps some day we shall be able even to estimate the exact amount of fuel and oxygen which are consumed during the elaboration of a great thought or the solution of an intricate problem in mathematics.

CHAPTER XXIII

UNCOVERING THE MACHINERY OF THE BRAIN

From very ancient times the kind of work done by the brain was known. It was a matter of common experience that when a man was struck a severe blow on the head he immediately lost control of all his muscles and fell down in a heap; he could no longer speak, see, hear, or feel; he became unconscious. Men in ancient times therefore concluded that the brain, which fills the skull and is injured when the head is struck, was the seat of consciousness and of the will.

The ancients also knew that nerves were the pathways by which the brain could communicate with the trunk and limbs. They observed, when the nerves to a limb were divided, that the limb could no longer be set in motion by the will; nor, when such a limb was touched or injured, could any message be transmitted to the brain. In these earlier times the fibres of nerves were supposed to be minute pipes containing a fluid which served to convey messages to and from the brain. Every nerve pipe was supposed to be capable, as is a telegraphic wire, of conveying messages in either direction—to the brain or from it. The brain itself was regarded as a factory of animal spirits which flowed out into the body and returned within the nerve pipes. Such a theory gave the ancients a satisfactory explanation of why nerves were sent out from the brain and spinal cord to every part of the body. The nervous system was a means of endowing the body with animal life.

In less than twenty years Harvey blew the ancient

explanation of the heart sky-high and replaced it by the modern conception that the heart is a living mechanical pump. The heart is a simple and familiar kind of machine compared to the nervous system. Yet it was not until the close of the nineteenth century, when inventors succeeded in linking together the inhabitants of great cities and countries by means of telephone exchanges, that we became acquainted with a machine or mechanical system which was at all comparable to the central nervous system of the human body. Before that comparison became possible the exchange centres of the brain and cord had to be unveiled and the nerve cables unravelled.

In order that we may understand how medical men succeeded in unravelling the chief machinery of the brain and spinal cord we must make a short journey in space and time, so that we may watch some of the pioneers set out on their labours. The inquiries of John Hunter, made in London during the latter half of the eighteenth century, provide us with a suitable point of departure. To see him at work we must seek out Covent Garden in the heart of London—not the built-over busy market of to-day, but the open fashionable square which met the eye of young John Hunter as he entered it on a late September day of 1748, travel-stained from eleven days spent on horseback in his journey from Scotland. He seeks a house on the north side of the square where his elder brother has established a school of anatomy, and presently we find this rough sandy-haired Scot, a man of twenty and accustomed only to farm life, assisting in his brother's dissecting-room with great dexterity. We have only to visit this room a few years later—in 1754—to see the kind of man he is developing into. He has a dissection of the nose in front of him, and is tracing out the various nerves which end in its lining membrane. That dissection is still preserved in the Museum of the Royal College of Surgeons of England, but our interest must remain centred on the fact that, at the time we now visit him, Hunter is wondering why the same area of lining membrane should receive nerves from two sources—from

the first cranial or olfactory nerve and also from the fifth cranial nerve. If what he had been taught was true, namely, that all nerves carried the same kind of sensations or messages, and that such messages could pass along both to and from the brain in the same nerve, then Nature had done a superfluous thing in giving the lining membrane of the nose a double nerve supply. One nerve should have been sufficient. Hunter had already learned that Nature was an economical as well as an expert constructor, and that she must have had a definite reason for providing the nose with nerves from both first and fifth cranial nerves. He rightly concluded that these two nerves served different functions : the first or olfactory being for the detection of smell, the other—the fifth—for common sensation. He further inferred that the nerve from the eyeball could carry only sight-messages, the nerve from the ear only sound-messages, and nerves of the tongue only taste-messages. The rest of the nerves of the body he grouped together as a common kind, and evidently believed, as the ancients did, that they could carry messages in either direction.

We have gone to John Hunter, not because he made a great discovery about nerves, but simply because he realised, what other men failed to see, that the manner in which nerves are distributed to the body cannot be explained unless it is supposed that they serve different offices.

We are now to watch another young Scotsman make a discovery of the greatest importance concerning the machinery of the nervous system. In 1804, eleven years after John Hunter's death, Charles Bell arrived in London from Edinburgh, where he had been trained as an anatomist and surgeon. He was unlike Hunter in many ways—very attentive to outward appearances and somewhat of a dandy in the matter of clothes. He had already passed his twenty-eighth year on his arrival in London ; he was poor, ambitious, and highly educated ; his sole hope of success lay in the publication of a manuscript he carried in his travelling valise. It was a treatise

on the muscles of expression, beautifully illustrated by drawings done by his own hand. He found no warmth of welcome in London, but he elbowed his way, and when almost at the end of his resources had the audacity to take the lease of a big ramshackle house in Leicester Square, where he put up his plate, and spent almost his last shilling in fitting the boy, who had to open the door for patients who rarely came, with a blue coat bedizened with brass buttons. He opened a private school for medical students, and we are to visit him in 1811 while he is giving his students a demonstration on the central nervous system of the human body. We find him puzzling over Nature's craftsmanship just as Hunter did. "Why," he asks his students, "should a spinal nerve have two roots? If both serve the same office, then why are they not united in one root?" He announced that he was convinced there were two roots because two pathways were necessary—one for messages going out from the cord, the other for messages coming in. He inferred that the hinder root was for incoming or afferent messages, because the nerves from the eyeball and from the ear, which had to carry only incoming messages, ended, as posterior roots did, on the hinder side of the brain-stem. The anterior root must then be for the outgoing or efferent messages which set muscles in movement. He concluded, on this basis, that the hinder part of the spinal cord was concerned in carrying messages to the brain, while its front part was for conveying impulses from the brain to the muscles.

If Charles Bell had been an ordinary man he would have remained satisfied with the guess he had made, but he was an anatomical detective of the highest rank. He followed up the clue he had thus hit upon. He pricked or stimulated an anterior nerve root in a living animal; the muscles supplied by the nerve contracted; pricking the posterior root, he found, had no result. He then cut the anterior root; the muscles supplied by the corresponding nerve were paralysed, but on cutting the posterior root no definite effect was detected. His guess

was right; each root served as a pathway for a definite class of message. Bell was excited by his discovery; so he well may have been, for he had succeeded in showing not only why spinal nerves had two roots, but that the ordinary nerves of the body contained fibres of two kinds: one which carried messages outwards, and another inwards. There was, in his opinion, a circulation of nerve messages. His great service, however, was in showing men a method by which the machinery of the nerve system of the human body could be unravelled.

Bell tried to discover Nature's secrets in much the same way as detectives follow up a criminal clue. He tried to explain appearances. Now, almost at the same time, or a little later to be quite accurate, as Bell was making his discoveries in England, a great French physiologist—Magendie—set out to discover why spinal nerves had two roots. He went about his work in quite a different way from that pursued by Bell; he made no preliminary guesses. He started away by cutting first one root, then another, and noting exactly what happened. He proceeded to collect facts by pure experiment and observation. His proofs that the nerve roots serve different functions were more convincing than those which Bell had brought forward, and hence we often find that men who have no sympathy with the detective way of finding out Nature's secrets give the whole credit of this important discovery to Magendie.

In 1826, when Charles Bell was reaping some of the rewards of his labours, there was another arrival in London which demands our attention for a moment. Dr Marshall Hall, a very clever and alert Englishman, suddenly abandoned his practice in Nottingham and settled as a physician at No. 15 Keppel Street, near the British Museum. We are to visit him there and witness a discovery which shed a new light on the nervous system. We find him in his consulting room, with his eye glued to a microscope, watching the capillary circulation in a lizard's lung. He has occasion during his research to cut off the lizard's tail, and is surprised to

notice that each time he touched it with a needle the tail wriggled. There was nothing new in this observation ; men had done and seen the same thing before. The question, however, which Marshall Hall asked himself was new. "Why," he asked, "should the muscles of this detached piece of tail contract when I merely touch the skin?" He observed that the lower end of the spinal cord lay within the amputated part ; he destroyed the cord, and then on touching the skin as before, nothing happened ; there was no wriggling. He then went on to carry out researches which showed that the spinal cord was not merely a nerve cable, as physicians then supposed, but the seat of a machinery which could start and control many purposive muscular movements. He showed that this machinery was set going by messages carried to it by ingoing or afferent nerve fibres, and that orders were dispatched along outgoing or motor fibres. He unfolded a reflex action—a "touch-button" machinery—in the spinal cord and brain stem. His discovery could not have been made if Charles Bell had not shown the way, but of the two discoveries Hall's proved the more important.

We have not yet finished with young medical men arriving in London and promptly setting out to make important discoveries about the nervous system. In 1845, when Dr Marshall Hall had become one of the most successful and most maligned physicians in London, Dr Augustus Waller commenced the practice of his profession in Kensington. He had pursued his studies in Paris and learned the value of the compound microscope —then being perfected—as an instrument for unravelling the secrets of the human body. While waiting for patients, he occupied his leisure hours in studying the almost transparent tongue of the frog to discover how juices of the food reached the terminals of the nerves of taste. On one occasion he was surprised to notice that the fibres of a nerve, which he had divided a few days before, were rapidly becoming broken up—undergoing degeneration. He noted that the degeneration ceased

at the point of division ; from that point to the brain the fibres remained intact. What proved still more surprising to him was the fact, that presently the degenerated fibres were replaced by a fresh set which grew out from the end of the cut nerve. This was a new light on nerves ; if they were cut, they withered and died just as branches do when they are lopped from a tree. Like branches, too, they can be replaced by the outgrowth of new ones. No other structure of the body behaves in this manner when divided.

The discovery which finally revealed the machinery of the nervous system was made not by medical men at all, but the mechanicians who in the early thirties of the nineteenth century converted the compound microscope into an efficient instrument for research. Methods were soon invented for cutting small slices of the brain and spinal cord so thin and translucent that they could be studied by the microscope. Then came the discovery of staining, of treating microscopic sections with dyes which brought out their structural pattern. These were the means by which the structure of the nervous system were unravelled.

Although the discoveries which Schleiden and Schwann had made in Berlin in 1838–39 convinced everyone that the human body, like all living matter, was made up of innumerable microscopic units or cells, yet at first it was difficult to believe that a nerve was made up of separate particles or cells. When a nerve thread was teased out by needles into its finest elements and these were examined under the microscope only delicate white fibres, each about $\frac{1}{2000}$ of an inch in breadth, were seen, packed in bundles like wax tapers in a box. Each fibre had its central wick or axis cylinder ; then came the wax-like substance—myelin—which surrounded the wick ; then the outer transparent wrapping or sheath. Nowhere did the fibres seem to be interrupted or come to a sudden end. A microscopic fibre, which commenced in the skin of the sole of the foot or in the palm of the hand, seemed to pursue an unbroken course until the spinal cord was

reached. Nerve fibres were laid down in the body in the same continuous and systematic way as men learned to lay telephone wires. There was no indication that nerves were made up of independent units or cells. In the brain, spinal cord, and in ganglia, however, units were discovered of the most diverse kinds. Anatomists noticed that these units or cells gave off branches. Some units seemed to have the appearance of microscopic carrots, with feathery processes or dendrites passing out from one end and a long tapering root ending a fibre-like continuation from the other. It was suspected at quite an early stage of microscopic investigation that every nerve fibre ended in a nerve cell, but that was not fully proved until 1885. In this year Professor His of Leipzig had finished a long study of the changes which take place in the spinal cords of developing human embryos. He found that the brain and cord were at first made up entirely of units or cells. He detected the roots of spinal nerves in the process of development. The fibres which make up an anterior root began, he observed, as sprout-like outgrowths from a colony of units within the cord ; a nerve sprout grew out from a cell or unit just as a tender shoot does from a sown wheat grain. The sprouts spread outwards exactly in the direction which led them to the part they were designed to supply. How they are guided we do not yet know. They grow out when the human embryo is very small ; even the nerve sprouts which form the nerve fibres to the muscles in the sole of the foot have not far to go. The fibres of the posterior root, Professor His observed, were also formed as outgrowths from units or cells. The colony which gave rise to them lay outside the cord and ultimately became included in the swelling or ganglion of the posterior root. Almost at their appearance the outgrowths of the hinder cells divided into two branches : one passed into the substance of the spinal cord and crept up towards the medulla, ultimately establishing many connections with elements of the cord (see fig. 47B) ; the other division grew outwards and, in company with the corresponding anterior root fibres, reached its right

destination, which we shall suppose in this case to be the skin of the sole of the foot. Thus the muscles of the sole as well as its skin become linked directly to the machinery of the spinal cord by means of nerve wires. Many uncertainties were cleared away from the nerve system by the discoveries of Professor His. We became assured that every nerve fibre is simply an outgrowth or branch of a nerve unit or cell. Besides sending out a main process or fibre from one end, a cell-unit in the cord or in the brain always threw out from its opposite end a series of shorter branches or antennæ—dendrites they are called,—which we shall see are of the utmost consequence in the mechanism of the brain. The meaning of Dr Waller's discovery became also quite clear. Nerve fibres die when they are divided because they are merely prolongations from mother units; they die when separated from their source, just as a finger dies when it is amputated. Further, the machinery of the whole nerve system is constructed on a unit system. The units differ in size and shape; the antennæ vary with the particular duty which units have to carry out; the fibre processes vary in thickness, length, and in manner of insulation. In one region we may find the units grouped in great masses, while in another they are scattered to form small stations. The fibres may form great trunk cables or mere meshworks. But everywhere throughout the whole nerve system we can be certain that we are dealing with a system composed of units formed on a common ground plan. In the next chapter we are to see how far we can apply the conception of a telephone system to the central nerve system. There is a great temptation to regard the cell units as microscopic batteries and the fibres connected with them as wires. But for reasons which will appear as we proceed, we prefer still to speak of the units as "operatives," meaning thereby that they also share in carrying on the work which operators do in telephone exchanges.

CHAPTER XXIV

AUTOMATIC TELEPHONE EXCHANGES

At the conclusion of the previous chapter I undertook to compare the organisation which is found in the brain and spinal cord to that seen in an extensive telephone system. It would have suited our purpose very well to have gone on board a great battleship and learned there how the work of the whole crew is regulated from the captain's quarters by telephone and other means. The captain's quarters constitute the cranial chamber of a battleship. There the brains are placed which are ever receiving information and dispatching orders. The work done on the bridge, within the gun turrets, in the engine-room and stokehole, and in the stewards' quarters, are timed and regulated from the ship's cranial chamber. The various services on a battleship have their representatives in the organisation of the human body. Or we might have selected our example from France and examined the telephone system which is laid down to link a general to the army under his command. Either of these examples would have answered our present needs excellently had it been our purpose to work out the telephone system of the body in detail. That, however, would have led us too far afield. All that we can do is to take a glimpse at one or two of the complex exchange systems used in the human body. For our representative sample we shall go neither to a battleship nor to an army, but to a smiling rural English town where the local exchange, managed by a single operator, serves the needs of three hundred subscribers. The subscribers, if they desire, can make

trunk calls and get on to subscribers attached to distant centres.

If you should happen to visit this provincial town, quiet and pleasant enough, you will be surprised to find out at the railway station that the town itself is some miles distant, and if you require a conveyance then you must enter the telephone box and get into communication with the local jobmaster. You take the receiver down and listen. Quite a lady-like voice asks, "What number, please." Through the transmitter you explain you do not know the number, but you want to get into communication with the jobmaster. You may almost hear the operator insert the connecting plugs which put you through to him. His bell rings until his wife comes and takes your order. In half-an-hour you are rewarded by seeing a comfortable carriage draw up at the station gate. We have seen a bolus of food, on reaching the pharynx, use a similar system to procure a conveyance—at least a means of transport (p. 175). When thrust from the mouth a bolus comes in contact with the lining membrane of the pharynx, which is beset with automatic transmitters of the "touch-button" kind. Mere contact is enough to set urgent messages streaming into an exchange in the medulla; the connecting plugs, which effect connections automatically in nerve exchanges, transmit these messages to the units or cells—jobmasters or drivers—which start and regulate the pharyngeal carriages; these driver units issue their orders, and the bolus is immediately seized and carried along the first stage of its journey towards the stomach.

We may cite one or two other examples which illustrate the telephone system of the human body. No part of the body is more thickly studded with automatic transmitters than the skin of the sole of the foot. When we are standing and walking messages have to be dispatched informing and warning the balancing muscles of the limbs and trunk concerning the poise of the body on the feet, for, as we sway this way or that, the pressure on the skin and on the transmitters is altered, and messages are thus

automatically dispatched.[1] These pressure transmitters work very quietly as long as we merely press on them, but if we touch them lightly—if we tickle them—then they dispatch messages of the most imperious kind. These messages stream into the usual exchange centre, one situated almost at the lower end of the spinal cord. In the exchange they are immediately "put through" to the units which control and drive the great muscular engines of the thigh and leg. The muscular engines spring into activity and the foot is withdrawn immediately from the source of irritation. Try as we will, we cannot prevent these tickling messages from forcing a way through the exchange centres. And yet the will, as we shall see, has free access to the spinal centres and can use them for carrying out planned and deliberate movements.

Another example will suffice to illustrate how extensive the telephone service of the body is. A particle of dust is blown into the eye; its arrival is immediately announced to two exchanges; through one of these the incoming messages are transmitted to a central station some distance off, occupied by the driver units which can shut the eyelids. These driver units keep the eyelids shut as long as irritant messages come through from the eye; when the foreign particle is removed the messages cease and the driver cells sink into their usual state of wakeful quiescence. The particle of dust also sets up another group of messages, one which is transmitted to a small local exchange in communication with the lachrymal gland. The messages thus transmitted send the lachrymal gland into a state of activity; tears stream across the eye with the intention of washing away the offending particle of dust. Even when that has been got rid of, if damage has been done, the flow of tears continues as long as the irritation lasts. Thus Nature employs a kind of telephonic system for many and diverse purposes in carrying on the work of the human machine.

Having just seen the kind of office served by telephone systems in a provincial town and in the human body, we now turn to compare the units or elements of which they

[1] See Appendix N, p. 329.

are built up. In fig. 46 a nerve and telephone unit are contrasted. In a telephone system a unit is made up of (1) a *transmitter*, the instrument which takes up our words and turns them into electrical messages; (2) a long stretch of copper wire, which carries messages from the transmitter to the exchange; (3) an electric battery, which pours an electric current along the wire and thus makes it alive; (4) an *exchange terminal.* These four elements make up a telephone unit. Each subscriber is connected to an exchange by such a unit. If one subscriber wishes to communicate with another, then the

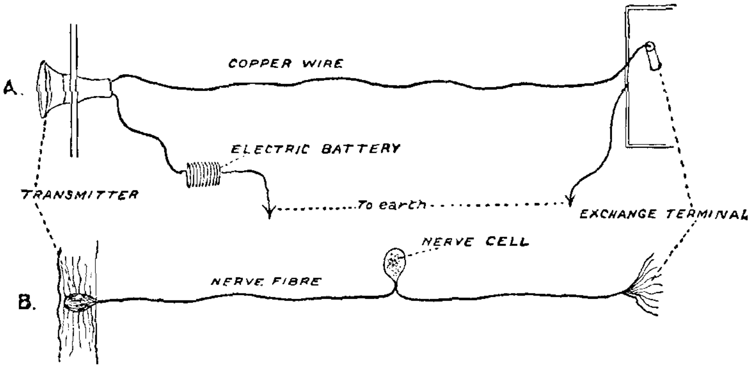


FIG. 46.—Plan showing the corresponding elements in a telephone and in a nerve system. A, Unit of a telephone system. B, Unit of a nerve system.

exchange terminals of their respective units have to be linked up. Engineers have discovered a method of having connections made at exchanges by automaton operators, but the automaton has to be worked by the subscriber who wishes to dispatch a message. In the local exchange from which our example is drawn, a living operator receives the subscriber's call and by means of switches or connecting plugs puts him through. The caller's message thus passes over the elements of at least two units to reach its destination. (5) A *receiver* to convert electrical impulses into sound waves, and thus render messages transmitted along wires into words. The corresponding elements in a nerve system, shown in fig. 46, B, are: (1) a transmitter or *receptor*, a contrivance

for the dispatch of messages. The form shown in fig. 46, B, is the kind used near joints for transmitting pressure messages. Messages are dispatched whenever pressure is applied to the transmitter. It is not sensitive to sound waves. There is a wealth of transmitter patterns in the human body. The retina of the eye is studded with one type; the ear with another; the nose and tongue have each their peculiar design. Muscles and tendons, as well as joints, are closely set with transmitters of the kind shown in fig. 46, B. They serve only for the dispatch of pressure messages. Every movement we make sends thousands of messages through these pressure transmitters. (2) A nerve filament or wire to carry messages from the transmitter to an exchange. Man has drawn copper into fine wire to serve for the carriage of messages from one point to another. For the same purpose Nature has drawn out the substance of nerve corpuscles or cells to form microscopic filaments or fibres. She leaves, as is shown in fig. 46, the filament attached to the parent cell, which, in the instance shown in fig. 46, B, is a cell stationed in the ganglion of the posterior root of a spinal nerve. (3) But what of the battery which causes a current of electricity to flow along the copper wire and thus makes it alive and fit to carry messages? What corresponds to a battery in the nerve system and makes the nerve filament alive and fit to carry messages? The nerve unit or cell maintains the filament alive and thus corresponds to a battery. But a nerve unit differs from a battery in this sense; it sends out no flowing current; the unit and filament are pulsating and throbbing with life from end to end, and it is because of its vital molecular movements that a nerve filament is capable of transmitting messages. (4) Then we come to the fourth element of a nerve unit system—the *exchange terminal.* It consists of a branching system of most delicate filament, quite different from the simple exchange terminal of a telephone unit. As to the fifth element, the *receiver*, it is not represented because it is unnecessary, and for this reason. Messages travel over telephone wires

as pulses or waves of an electric current. The waves have to be turned into sound waves and words before they can serve as human messages. We shall see that the subscribers to nerve exchanges can read the messages in the form in which they are transmitted over the wires ; they need no receiver to make them audible and intelligible.

Having thus contrasted the elements which make up a unit in a telephone and in a nerve system of communication, we now proceed to see how they are built up to form exchanges. In figs. 47A and 47B only two units of an exchange are represented ; whereas even in a local exchange, whether it be one in a provincial town or its counterpart in the spinal cord, there are really hundreds of subscribers and units. We have chosen only two units for simplicity's sake. In the telephone exchange two units are seen to be joined within the exchange ; over these two units messages can be given or received by their respective subscribers. In the nerve system two units are also shown. The unit which is furnished with a transmitter can only carry ingoing messages ; it has no receiver at the outer or calling end. The unit to which it is connected has no transmitter, only a receiver of a peculiar kind, one which changes nerve messages into orders or stimuli which set muscles in motion. It will thus be seen why I did not wish to look upon the bodies of the nerve cells as mere batteries. The two nerve units represented in fig. 47B are of different kinds. The nerve cell in connection with the transmitter is a "signaller" cell ; its unit has to do with messages which pass to the exchange. The nerve cell placed within the spinal cord and connected with the receiver or end plate of a muscle cylinder is a "driver" cell. It has to do only with outgoing messages. The messages which reach it are turned into orders which start, regulate, or stop muscular engines. The telephone units can convey ingoing as well as outgoing messages, but it will be seen that nerve units serve either the one purpose or the other. We must look on the nerve cells as more than mere batteries ; they have in them also the function of subscribers.

But what of the exchange operators? Nerve exchanges are automatic. Messages pass from the exchange terminals of a signaller unit straight to the exchange terminals of a

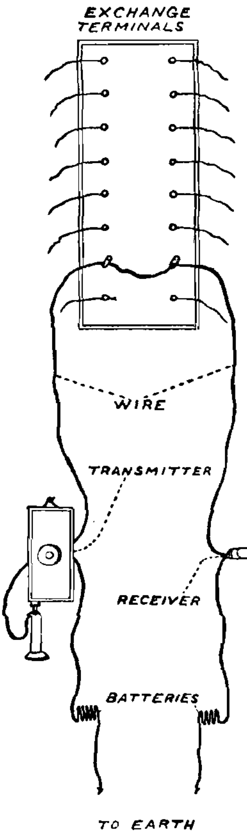


FIG. 47A.—The arrangement of two units in an exchange of a telephone system.

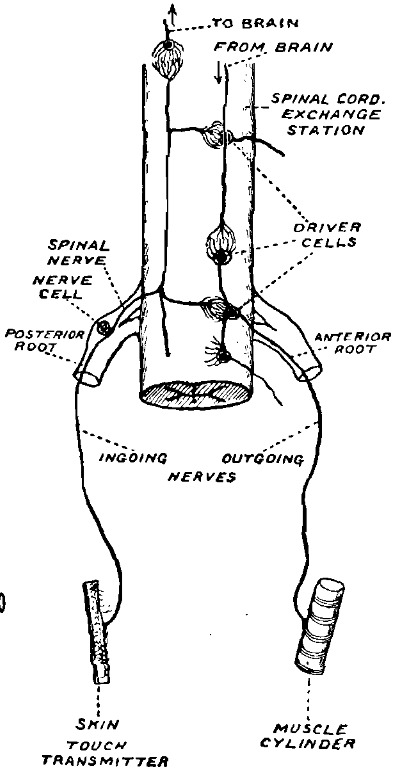


FIG. 47B.—The arrangement of two units of an exchange in the nerve system of the spinal cord.

driver unit (fig. 47B). Their terminals are in contact only. There are many exchanges, however, where there are really operators at work—"operative" units, as I prefer to call them. In most of the exchange centres

of the human brain and spinal cord "operatives" or "shunt" units will be seen linking terminals in one exchange to terminals of driver units in an adjoining exchange. Such operatives might well be named relay units. It is in the manner just outlined that the hundreds of exchanges within the spinal cord are built up.

From the head or body of one of these connecting or "operative" units is thrown out a series of branching antennæ or dendrites; from its other end emerges a nerve filament which soon branches out into a series of terminals. The antennæ and terminals represent the switches or plugs by which the operatives "put through" messages which pour in upon an exchange when the body is in action. In fig. 47B only two of the thousands of wires which reach the exchange are represented. One of these will be seen to spring from the main wire or fibre we have followed through the posterior root ganglion of a spinal nerve to the spinal cord. That wire, having given off a side branch to the small exchange centre we are considering, passes along the cord for the purpose of carrying trunk calls to the brain. In the exchange of a provincial town all trunk calls have to pass through the local exchange; here we see Nature making an improvement by giving each subscriber access to metropolitan as well as to local exchanges. In this spinal exchange which we are now considering a wire from the main executive exchange of the body—the seat of the will—is seen to arrive and terminate. The will also uses local exchanges for the distribution of orders. The operatives in a local exchange of the spinal cord receive messages coming both from local subscribers and also from the government or brain, and it is their business to put such messages through to their proper destinations. In the instance cited a few pages back the local operator put a call through to a jobmaster who lived some miles from his exchange. Nature has arranged her system quite differently. She has brought the nerve units which control her conveyances—her muscular engines—almost within the exchange itself.

The brigades of driver cells which control the muscles of the body, instead of being placed beside their engines, are brought up and quartered in the precincts of the exchange from which they receive their orders. Hence the operatives within the exchange can transmit the messages received for the driver units almost directly to them (fig. 47B). The driver units having received their information or orders from the signaller cells either directly or through operatives connected with their exchange, dispatch messages to the muscles under their control.[1] The essential differences, then, between a telephone and a nerve system are: (1) That telephone subscribers who carry out orders —who supply our needs—are situated in any part of a town supplied by a telephone system, whereas in a nerve system they are assembled almost within the exchange, and therefore have to be linked to their engines and laboratories by wires or nerve filaments, which in reality represent an extension of the system. (2) The manner in which telephone and nerve messages are carried is different. Telephone wires can carry messages because of the electric current which is made to flow along them. The transmitter into which we speak interrupts the flow of the current, and thus the vibrations of our voices are carried along the wires as pulses or waves of the electric current. In the human body the wires are living and pulsating because of the slow vital combustion which is steadily maintained in their substanee; the messages which are set going within them when a transmitter is stimulated are carried as self-propagated waves to the exchanges. They travel much slower than electrical messages, their rate being about 4 miles a minute. It takes one-hundredth of a second for a touch-impulse which is applied to a transmitter on the pulp of a finger to reach a man's brain, but for the needs of the body that is quick enough.

We have made a rapid comparison of the manner in which local calls are dealt with in an exchange situated in a provincial town and another placed in the lower end of the spinal cord—an exchange whose subscribers are

[1] See Appendix C, p. 287.

placed in the sole of the foot. We are now to compare the methods of dealing with trunk calls. We shall suppose an official from the Ministry of Health has had reason to visit the town in which our local exchange is situated because of the outbreak of an obscure disease. He wishes to communicate with headquarters in order to report what he has found and to have certain orders sent out from the Ministry which will waken up a lethargic local authority. He rings up the local exchange and asks to be "put through" to the Ministry. He has to wait some time, for the local operator has to get in touch with the exchange in the nearest county town; the county town exchange has to get through to another in London; two others have to be negotiated before the provincial message has a straight run through to the official quarters of the Ministry. The message thus transmitted by the aid of operators placed in five different exchanges sets into operation the official machinery of the Ministry, with the result that a peremptory order is dispatched to waken up the local authority of the provincial town.

Let us see how trunk calls are managed in the nerve system of the human body. A sharp fragment of stone falls within a shoe and presently works its way under the foot. With each step it presses against some of the transmitters in the sole and sets up messages, at first giving a mere feeling of discomfort, but afterwards becoming more urgent, giving a sense of intolerable pain. The brain is set into operation, with the result that the movements necessary for unlatching the shoe are undertaken and the offending body is discovered and removed. The instance is not unlike that which we have been following in connection with an epidemic in a country town. In the human body, however, the wire which carries messages from the sole of the foot does not pass through the local exchange in the spinal cord; it sends off merely a side branch to one, two, or more spinal exchanges and passes up the spinal cord until it reaches the first great exchange of the body—one which is situated where the spinal cord becomes continuous with the brain stem. Here the

messages from the sole of the foot are automatically switched on to main trunk cables which carry them to a second exchange centre—one situated in the great masses of grey matter placed within the cerebral hemisphere (see p. 239). It is in these grey masses that the messages from the sole rise up into the field of consciousness as painful sensations. The executive exchanges or departments of the brain lie still further on ; they are spread out in the grey matter which forms the cortex or rind of the cerebral hemispheres. Hence the messages which have reached the basal masses and given rise to the sensation of pain have to be transmitted by a third relay of wires to the cortex of the brain before steps can be taken by the executive departments. To obtain relief the "driver" cells of the cortex have to be set in motion. We have already seen that the "driver" units, which exercise a direct control over muscular engines, are grouped round the local exchanges of the spinal cord. These driver cells we meet with in the cortex of the brain are " master drivers " ; they control the driver units in the local exchanges, and combine their actions so that the muscular engines carry out the movements which are determined on by operations effected within the exchange systems of the cortex. The cortex of the human brain is by far the most elaborate central exchange in creation.

It is into this exchange, then, that messages dispatched from the sole of the foot pass, after being switched through two great exchanges and having travelled over three relays of nerve cables. Arriving in the cortical exchange they set going a machinery which leads to the master driver cells taking charge of the movements of the body. It was they which controlled the driver units of the local centres during the body movements which led to the removal of an offending stone from the shoe.

The reader will probably be surprised to know that the bulk of the messages which stream through the exchanges of the nervous system have nothing to do with the kinds he is familiar with—messages which give the sensation of touch, pressure, pain, heat, or cold. The majority

are mostly silent muscle messages sent up to the driver cells and to the master drivers to keep them informed of the state of the muscular engines under their control. From start to finish of a body movement the driver cells have to be deluged with information. An enormous special exchange has been built for dealing with muscle messages—the cerebellum. If the cerebellum is injured, then the movements of the muscles and of limbs are no longer timed and co-ordinated. Engineers have designed and applied automatons to take the place of exchange operators. Such exchanges are called automatic, but they are really not so, for the automaton in the exchange has to be worked by a subscriber before he can get his message through to its right destination. On the other hand, Nature's exchanges are automatic.

In one respect the telephone system invented by man has an advantage over Nature's system. As long as the batteries keep up an electric current along the wires they will carry messages hour after hour or year after year without sleep or rest. Nature's wires are different. Messages are propagated along them at the expense of their own substance and of the substance of the living units of which they form a part. If worked hard the available supply in nerve cells and fibres runs low. So that rest and sleep are necessities for them; it is during rest and sleep that our brain and nerves recuperate.

We have frankly admitted, three chapters back, that the traces of a nervous system in a motor cycle are miserable travesties. The wire which carries the electric current to the sparking plug serves the same purpose as the nerve which carries motor impulses to a muscle. The gearing mechanism which times the opening and shutting of valves and the firing of the electric spark does serve a purpose, comparable to that carried on by the cerebellum, which has to time over 200 pairs of muscular engines.

To find any system which is comparable to that represented by the human brain, spinal cord, and nerves, we have to study the great machines which are composed

of living human units and make up the nations which lead in the van of civilisation. We can get light on the nervous organisation of our bodies if we look for a moment at the manner in which the nerve system of a nation has been evolved. Time was, and that not many centuries ago, when a man had to supply all his personal wants: he had to be farmer, fisher, hunter, tailor, shoemaker, carpenter, blacksmith, builder, warrior, and surgeon. The chieftain regulated the small tribal machines of which the primitive individuals formed loosely knitted parts. Then came the modern period of specialisation, and the work formerly done by one individual was parcelled amongst a thousand specialists or more. In this evolutionary movement a great group of individuals or units became set aside or specialised to serve as a brain or government for the national machine—to receive information from all its parts, and to issue orders to all. The brain came to have at its disposal certain executive departments—a navy, an army, judges, magistrates, and police. Now Nature in building up the human machine has pursued a course not unlike that which has led to the evolution of a modern national machine. In her primitive animate designs the living units were self-supporting; each could procure and assimilate its own fuel; it looked after its own supply of oxygen; it carried out its own movements; it kept up its own circulation; it could dispatch a message from one part of its minute body to another part. Then came evolutionary specialisation and the welding of all the differentiated units into a machine. Some became fuel attendants; others took a hand in pumping the blood, or helped in its ventilation, or joined the police or sanitary services of the body machine. Then in one group of units the power to contract, which was inherent to a slight degree in the primitive type, became their special prerogative; they were converted into muscle spindles or cylinders. But the group which interests us most here is that which was set aside to form a nervous or governing service. The primitive animate

units were sensitive to impressions, the stimulus which caused one of them to contract, spread slowly as a wave, from the point which was touched. In the specialised governing units which make up a nervous system, sensitiveness and the power to conduct a message wave became their sole duty in life. These highly specialised governing units were grouped together in great central departments, which are represented by the brain and spinal cord—the governing system of the human machine. In our bodies one unit out of every fifty is a government servant or master.

The high degree of specialisation seen in modern national machines has been rendered possible by inventors who discovered methods of improving communication. A modern nation could not move as a machine if it were deprived of its roads, its railways, its steamers, and its cable, telegraph, and telephone systems. In recent centuries one improvement followed fast upon another, each serving to link the individuals of a nation more closely together so that they could act as a single machine. In early days paths beaten by the feet of British natives had to serve the tribal messenger; roads and mail-coaches came in due season; railways and telegraphs followed, and quite recently appeared the all-pervading ramifications of the telephone system. We have seen that the human machine has passed through corresponding phases, from the slow postal traffic carried in the blood circulation to that triumph of rapid communication—the nerve system. There is one striking difference, however, in the organisation of a national machine and a human machine. The government officials of a nation, as well as plain citizens, use freely both telephone and telegraph systems in carrying out their duties. But in the human body the whole system of rapid communication has been made a government monopoly. All its telephone exchanges are manned by government officials. The humble units which carry on the productive industries of the body may dispatch messages which are intended for another set of workers, but these

messages have to be submitted to the central government and duly approved or censored before they are passed on to their destination. If the transport units which conduct the alimentary traffic go on strike and wish to call out the units which prepare the supply of fuel for the body, they cannot send their message direct: it has to pass through the government telephone exchanges. To modern minds it may seem that the administrative units take an unfair advantage of the monopoly controlled by them. Nothing can happen in the commonwealth of the body without it coming to the knowledge of the central administration. And yet the population of living units included within the human body far exceeds in numbers the total population of the earth. And they are ruled with unmatched ability. Is the administrative system of the human machine the ideal towards which the modern national machine is tending? There are signs that this is the case.

Is there a wireless installation in the nervous system of the human body? We are certain only of this much: we are totally unaware of the wireless waves which, in these modern times, fill the air day and night. Their messages beat against our eyes, ears, and brains, and yet we are unconscious of them until we take special contrivances which can convert these messages into sound waves. We cannot see X-rays until they are turned into light rays. It seems reasonable to conclude that if wireless messages had been emitted by living things, or by the surroundings among which life was carried on, that Nature would have provided her higher creations with contrivances for converting wireless waves into nerve messages. She has provided contrivances for turning light and sound waves into nerve messages. There is thus no evidence which leads us to believe that Nature has ever used her wireless waves to provide a communicating system for linking living units together. Herein Man seems to have stolen a march on Nature.

CHAPTER XXV

IN THE REPAIRING SHOPS

We medical men are wayside repairers of the human machines which break down on the road of life. In many ways our day's work is very like that done by our friend who carries out the repairs at a neighbouring garage. Both of us are good or bad workmen according to whether we know well or ill the use of every part of the machine we are called on to repair. Both of us grow more skilled as we become more experienced, for human machines, like motor cars, have their weak points, and only experience makes a man thoroughly familiar with them. Both, too, are sometimes shouldered with burdens of undeserved blame when they really merit a high reward for the application of patient if ineffective skill. Then by way of compensation they sometimes receive a large fee and grateful thanks for executing a very ordinary piece of repair. A patient seeks our aid who finds life intolerable because of giddiness in his head. A small plug of wax is removed from an ear passage by the use of a syringe and tepid tap water; he is instantly restored to his normal life and comfort. He thinks a miracle has been performed upon him, whereas he has merely received a routine attention. The mechanic at the garage may earn a reputation by putting an unworkable car to rights when others had failed by merely removing a little water which had somehow gained admission to the carburettor.

It is not my intention, however, to draw a comparison

between the breakdowns of motor vehicles and human machines, nor to point the lesson that careful driving and periodical overhauling will secure safe running in both cases. I am writing this chapter because it is in the repairing shop that we learn the essential difference between machines of Nature's design and those of man's invention. We are going to see that only Nature can repair the machines which Nature has made. The good physician and the skilled surgeon are only good and skilled in so far as they know the way in which Nature works her cures. They can assist her to such an extent that it can be said justly and truly that they save life and restore health. The skilled mechanic is in quite a different position. He can do much more for his machines because they have been designed and made by workmen like himself. He designs, forges, and welds his bolts and shafts, remetals his bearings ; he is no mere assistant to a higher power, but a Vulcan in his own right.

We can best understand the difference between the repair of a motor car and a human machine if we cite a few instances culled from actual practice. In an early chapter we have compared the tendon (see Plate II.) of the muscular engine which moves the heel to the connecting rod which unites the piston to the crank-pin of an internal-combustion engine. Now, it is not a common accident for the connecting rod to break or the tendon to be ruptured, but it certainly does occur. The motor car comes to a sudden halt ; the human machine can still go limping along. Both machines have to go to a repairing shop or hospital. In the repairing shop, if the connecting rod is of a standard type and spare parts are available, then repair is easy ; a new connecting rod is put in place of the old. But the roadside repairer, if he is a real motor-car surgeon, must be able to make a new one or know how to forge, weld, and temper the old. With the human machine two courses are open to the repairer. If a skilled technician he will, like the mechanic, expose the ruptured part, stitch its torn ends together with silken loops, and then stitch up the opening

he has made in the skin. The modern surgeon is so certain of the absolute cleanliness of his instruments and fingers that he never fears the introduction of germs which may set up an inflammation that endangers his patient's life. He binds the mended limb with splints in such a way as to secure a free circulation of blood to the injured parts and at the same time to prevent such movements of the foot or knee as would undo his carpentry. But the surgeon does not really mend the rent in the tendon or skin by his stitches ; he only places and secures the torn or cut parts in their normal position. Nature has then to do the welding and the mending. Just watch how she goes about her work. First she keeps messages going from the injured part to the exchange centres in the spinal cord that prevent the patient from using his foot in walking and standing. Then she turns on the stopcocks of the vessels which supply blood to the site of the injury. Then, most wonderful of all, she sets the tendon-builders to work. The living units on each side of the rent or tear change their ordinary habits ; their lives are suddenly quickened ; they multiply rapidly, and thus breed new tendon units, which grow into the gap from each side and so bridge it with tender new tendon tissue. Subsequently consolidation commences ; the tendon units or builders give rise to fibres which gradually grow in strength. In six weeks or less Nature has welded the ends of the tendon so that the "connecting rod" of the heel can withstand all ordinary strains. From beginning to end of the undertaking Nature was the blacksmith ; the surgeon was the assistant : he blew the bellows and saw that she was not interrupted when at work ; he saved her trouble by bringing together the torn ends of the tendon, and hastened recovery by seeing that Nature's behests were observed by the patient. There are surgeons, however, who rightly maintain that repair is effected equally well if they merely bring the torn ends as nearly together as is possible by bending the ankle and knee and retaining them in a bent position. They obtain almost as quick and good repairs as surgeons who are more

active and daring. It will thus be seen that the mending of a broken connecting rod and the repairing of a ruptured tendon are effected by very different means. One is welded ; the other is healed.

Let us take another example. The axle of a motor car gives trouble ; there is a crackling noise in the bearings ; on exposing the axle the mechanic finds it scored owing to a broken ball-bearing. He removes the fragments and replaces them by a new bearing, and all then goes well. Now, in one of the main axles of the human machine a somewhat similar accident is apt to occur, particularly in strenuous young athletes. A cartilage of the knee-joint becomes ruptured and displaced. The knee cartilages serve as movable bearings to fit together incongruous moving surfaces of the joint. The result of such an accident is a sudden locking of the joint. Two courses are open to the surgeon. He may open the joint, just as a mechanic does the axle of a wheel, and stitch the bearings back into their proper position, or, if they are damaged beyond repair, he may remove them and trust to Nature replacing them. If he opens the joint his patient runs some risk, for a mistake may lead to the introduction of germs and consequent inflammation and stiffness of the joint. That is a risk which the skilled surgeon does not fear. But in this case, as in the last, there are surgeons who maintain that as good and as quick healing of the ruptured or displaced cartilages can be obtained by first replacing the fragments by manipulation of the joint. Having thus restored the parts to their right places, they bind the limb to a splint and leave the actual repairs to Nature. So equal are the results obtained by either of these methods that it is difficult to tell which is the better one. Certainly there are cases of long standing in which repeated and skilled manipulations fail to give relief and which can be set in the way to recovery by a surgical operation. But whether the surgeon succeeds by operation or by manipulation, in either case it is Nature who actually effects the repairs ; the surgeon is her skilled assistant.

The two instances just cited were selected from surgical practice ; we shall now take a case which may be described as being of a medical nature. A motor car is brought to the repairing garage because its driver complains of a lack of speed and power, especially in taking hills. In fact, the car becomes breathless on going up a steep incline. The repairing mechanic finds that the valves of the engine leak ; he grinds and resets them, and all trace of breathlessness disappears from the engine. A patient comes to a medical man complaining of breathlessness, especially on going upstairs. Now, such a breakdown may arise in human as in motor machines from many causes, but the skilled physician looks first to the state of the valves of the heart. He listens over the position at which he knows the great stem of the heart—the aorta—comes to the surface of the chest ; he notices that as the heart throws its charge of blood into that vessel there is a rough sound which should not be heard there, and that the sudden click which marks the closure of the valves and prevents the blood flowing back into the aorta is almost lacking. He concludes, therefore, that the breathlessness does not lie in a deficiency of the lungs, but in a defect of the body pump. The aortic valves, he knows, have become shrunk from disease. What is the physician to do in such a case ? What can Nature do ? Neither the physician nor Nature can open up the pump and replace damaged valves with new ones. Living valves cannot be ground and reset. Nature comes to the rescue in this way. She brings into operation her compensating mechanism ; the muscular engines of the ventricle have now to do double work or more, because part of the discharged blood falls back upon them. The muscular engines of the ventricle become thick and strong and are able to do twice their usual amount of work. The physician's duty is plain. He has to assist Nature as much as lies in his power. Such a patient has to nurse his heart—undertake only such physical work as lies easily within the effective capacity of his heart. If strict regulations are observed such a patient, as Sir James Mackenzie has

taught us to expect, may lead a quiet and useful life and reach a good age. It will be seen from this how different the conditions are under which the mechanic and physician carry out their office of mender. The mechanic is an active agent; the physician is Nature's oracle.

On the road of life both motor vehicles and human machines get damaged in collisions. Temporary repairs have to be effected on the spot. The wooden spokes of a smashed wheel may be temporarily replaced by splints made from deal boards, thus making it possible for the damaged vehicle to be taken to a repairing shop. The driver himself may have a thigh-bone broken. Temporary splints are applied and he too is taken to a repairing shop. But the manner in which the permanent repairs are effected is totally different in the two cases. The broken spokes of the wheel are replaced by new ones, and although there are plenty of spare discarded parts of the human machine to be had, they are of no use, for two reasons: first, because they are dead; and second, because there are no standard sizes—no two human machines are made exactly alike. The broken lever of the thigh has to be welded by Nature, and it will take her six weeks or more of steady application even if she is given the most suitable conditions for her work. One thing Nature cannot do; if the broken ends are askew she cannot straighten them out and restore the lever to its proper shape. The surgeon has to perform this service for her. The muscular engines of the thigh are torn and damaged and have to be coerced by the surgeon before he can replace the fragments into a good position. He may even proceed as a carpenter does when he has to repair the broken leg of a table—expose and brace the fractured ends by plates of dead metal or of living bone. That, however, is merely to hold the parts in position as Nature welds them. She proceeds to work by stages; the gap between the broken ends is first filled by a temporary scaffolding organised from the blood effused between the broken ends; then, very slowly, the bone-builders on each side of the breach are roused to an activity by a

mechanism which is not yet understood. The bone-builders spread into the temporary scaffolding and replace it in the course of a month by a rough and clumsy-looking ferrule of imperfect bone. In six weeks or seven muscular repairs have been effected and the bone ferrule has become strong enough to allow the thigh to be used lightly. It is only then, when the bone-builders become subjected to the stresses which pass up the thigh in standing and walking, that they become engineers as well as masons. As the thigh comes into use they rebuild and trim the temporary ferrule of bone, replacing it with properly designed props and struts to meet the strains and stresses of normal usage. It is in this slow manner that Nature welds the ends of a broken bone. The surgeon's part is not that of a carpenter, but of a magistrate-policeman ; he has to see that the bone-builders are not molested in any way whatsoever while in pursuit of their lawful vocations.

In the war motor vehicles as well as soldiers were knocked out of action by enemy bullets. At the base, well-equipped, extensive repairing sheds were erected for mending the motor transport ; great hospitals were fitted out for the repair of the wounded. No matter how foul and infected the missile may have been which damaged a vehicle, the hole was as easily patched as if it had been perfectly clean. It was otherwise with wounded human machines. Clean wounds, wounds which had escaped infection by the germs of disease, healed kindly. Nature healed them ; the surgeon had merely to serve as Nature's watchman. But if they were infected, then the surgeon had to come to Nature's aid. He had not only to cleanse them ; he had actually to cut out the dead and damaged tissues which afford disease-causing micro-organisms the material on which they thrive best. Even when the surgeon had done his utmost, infection sometimes got the upper hand, and the wound became the seat of a furious battle. Nature has been so prudent and far-seeing in designing her living machines that she has provided them with a most elaborate mechanism, not

only for healing wounds, but for repelling the germs which invade them. She mobilises her army of defence at the point of danger. She uses means which dope cr lower the vitality of the enemy so that they fall more easily a prey to her fighting forces ; she can also raise the power with which her soldiers carry out their attack. Medical men have studied closely the battles which are fought between the defensive forces of the body and the advance guards of bacterial invasions and have discovered means of assisting the defence.

But the means they have discovered and applied are those used by Nature. In this case again medical men assist recovery by playing the part of Nature's assistants. The rôle of the surgeon in the base hospital and of the mechanic in the base repairing shed are totally diverse.

We shall cite a parting instance to show how different the nature of living flesh is to that of dead metal. In previous chapters I have striven to convey some impression of the manner in which countless myriads of living units are linked together to form the human machine. I have also sought to make clear that the kind of society in which these units spend their lives may be compared to the social organisation of a highly governed modern state. Whether we are coal-miners, transport workers, farm-labourers, cotton spinners, or even men of "independent" means, we are, one and all, units in the organisation of a great machine. I must freely admit, however, that the units of the human machine are arranged upon a caste basis ; the laboratory attendants in the stomach and their descendants have to follow their allotted vocation during the lifetime of the machine. So it is with every system of the body ; there is a muscle caste, a nerve or governing caste ; there are bone-building and cartilage-building castes. The caste system is rigidly enforced by a mechanism which, unfortunately, we have not yet discovered. The units of one caste rigidly follow their special vocation and strictly observe the rights of neighbouring units belonging to another caste ; all do their best for the machine as a whole. This is the rule, but occasionally it

does happen that they not only break away from tradition but something very like mutiny occurs. In certain parts of the body—in the stomach, for example, or on the lips, in the womb or female breasts—there are certain castes which have earned a most unenviable reputation for the frequency with which they break through the bonds which keep neighbouring unit castes in harmony. The nature of these living units suddenly changes ; a war of caste breaks out. Instead of carrying on their traditional duties in peace and with mutual goodwill with their neighbours, members of one caste increase rapidly in numbers and break into the territories of surrounding castes. They wear down and destroy all opposition and eat their way into the machinery of the body, and ultimately destroy the whole machine. A caste mutiny on the part of a set of living units of the body we name cancer. My friend Mr Morley Roberts, who has given this cancerous manifestation of cell rebellion much close study, is of opinion that the living units of one caste are kept in proper restraint by the units of an adjoining caste and that when rebellion breaks out the fault lies not with the rebels but in the weakness of the neighbouring restraint. If that is so, then the discovery of the prevention of cancer will come to the man who finds out the manner in which Nature regulates the lives of the microscopic units of that most highly organised of all empires —the Human Body. In the right understanding of the Human Machine lie the keys to Health and Life.

APPENDICES

APPENDIX A

SIR JAMES DEWAR

I HERE allude to the Director of the Royal Institution—the late Sir James Dewar—who maintained the great traditions established in the Royal Institution by his predecessors, Davy, Faraday, and Tyndall. He died 27th March 1923, in his eighty-first year, having been actively engaged in research until within a week of his death. It was his great fortune to retain, unabated, his brilliant gifts of mind, his dexterity of hand, his warmth of heart, and his sense of humour until the end. Professor H. E. Armstrong has said of him: "As an experimentalist Dewar stood alone; there never has been a greater, probably none so great. Science lost in him a worker of a peculiar breadth of originality, a most fascinating character. How much the world has lost in his death it little knows." Men know him as the inventor of the thermos or vacuum flask; scientists will remember him for the powerful instruments he placed in their hands for unravelling the constitution of matter; but lecturers at the Royal Institution will recall him for the candour and kindliness of his criticism.

APPENDIX B

MUSCLES AS COMBUSTION ENGINES AND HOW THEY SERVE THE NEEDS OF ATHLETES

At the time when these lectures were given in the Royal Institution our knowledge of muscles was being rapidly advanced. Until then most physiologists believed

that every muscle formed in its substance a kind of fuel (which was named *inogen*). They believed that when a muscle contracted this fuel was oxidised or burned, the energy thus set free being used for performing work. They could in this way explain why it was that a man when he used his muscles, especially if he did hard work, required more oxygen; muscle fuel (inogen) was consumed or burned according to the amount of work done. They could explain, too, why the working body gave off more carbon dioxide; it is a product of combustion. They could explain why the body became hot when much work was done. They saw that in these respects a man's body behaves just as does an internal-combustion engine—such as that of a motor car—when it is made to do work. The quicker a car is made to run, the steeper the hill it has to climb, the more oxygen does it consume, the more carbon dioxide does it give off, and the hotter does the engine become. Further, physiologists knew then that the fuel of muscles was a combination of hydrogen and carbon just as is petrol, the fuel used for internal-combustion engines. When such a fuel is burned it is converted into carbon dioxide (CO_2) and water (H_2O). The fuel used for providing muscles with energy is glycogen, a carbohydrate substance with the composition, $C_6H_{12}O_6$. When one gram of it is burned, it gives off 3836 calories of heat—enough to raise the temperature of 3836 grams of water 1° C., and the energy or force thus set free is sufficient to raise a weight of 5332 tons to the height of 1 foot. Petrol is a better fuel than glycogen, or than glucose, a simple sugar into which glycogen is easily converted. When a gram of petrol is burned it gives off 7500 calories of heat—more than twice as much as does a gram of glycogen.

In 1916 discoveries were being made which compelled us to give up the idea that a substance is oxidised or burned in muscles during the moment of contraction. It is interesting now to look back and see how these discoveries came about. They were begun by Sir Walter M. Fletcher, now Secretary to the Medical

Research Council, but when he made his first discovery he was a young graduate working in the physiological laboratories at Cambridge. The experiments he was then making were of a kind which had often been done before. He was noting very accurately what took place in a very small and humble thing—a muscle cut from the leg of a frog. The muscle was living, for although the brain—the sentient part of a frog—dies almost at once, other parts of the body, particularly the muscles of the limbs, will remain alive for hours or even days. Hence it is possible to cut out and study a living muscle and note what happens when it is stimulated and thus made to contract. He watched and studied such isolated living muscles much as one might investigate a small internal-combustion engine—one made on such a diminutive scale that its machinery cannot be made out by the naked eye. Much could be learned of such an engine by noting how much oxygen it consumed and the conditions which caused it to increase the consumption, and particularly by observing how much CO_2 came off in a given time, and the circumstances which led to an increase of the discharge of this waste gas. Now this was the manner in which Sir Walter Fletcher proceeded to study the small live muscle of a frog. He had perfected a method of measuring very minute quantities of CO_2, for to make advances and discoveries we must always invent more perfect methods of investigation. Now, if our miniature internal-combustion engine were placed inside an air-tight box, which had been filled with a non-combustible gas, such as hydrogen or nitrogen, it would stop immediately; it would be "suffocated" because its supply of oxygen was cut off. This is exactly what Sir Walter Fletcher did with a frog's muscle, he placed it inside an air-tight box filled with inert gas; but he found it did not stop; it could still contract every time a stimulus was given to it. He did find, however, that a muscle in such a box tired very quickly; it became fatigued and soon was unable to contract, however much it was stimulated. When, however,

air was admitted to the box in which the muscle was kept, particularly if the air was rich in oxygen, the muscle began to recover, and was soon able to respond to every stimulus. It was clear from these experiments that a muscular engine differed from that of a motor bicycle in being able to work when its supply of oxygen was cut off.

Sir Walter Fletcher continued his studies of the isolated muscle of the frog, and, by 1902, he had assured himself of two things: (1) that it was not during contraction that most of the oxygen was consumed,—the muscle became greedy for oxygen when the contraction was finished; (2) that the oxygen taken in by a muscle at the end of a contraction was used for the combustion of some waste substance which was formed in the muscle during its action. This substance he believed to be lactic acid. In brief, he was convinced that a muscle became fatigued by the accumulation in its substance of waste products, formed during the act of contraction. He found that if oxygen were freely admitted to the muscle, then these products were consumed as soon as formed and the muscle remained capable of contracting as long as it could be kept alive.

In 1907 came the next advance. Sir Walter Fletcher and Sir F. Gowland Hopkins set out to discover how and when lactic acid was formed in muscles. They invented and applied a more accurate way of recognising lactic acid and of measuring its amount. They found it was formed only in living muscles, and that the more a muscle contracted the greater was the amount of lactic acid formed in it. They realised that somehow the formation of lactic acid was related to the act of contraction.

The next step forward came in 1909 when Professor A. V. Hill, who had been a pupil of Sir Walter Fletcher at Cambridge, applied another method to the investigation of isolated muscles. Sir Walter Fletcher had studied the combustion which took place in these engines by measuring their consumption of oxygen and their output of carbon dioxide. Professor Hill measured their com-

bustion by taking their temperature when they were at rest and then when they were in action. It is not an easy thing to measure changes of temperature in a small muscle. When an isolated frog's muscle is made to give a single contraction, its temperature is raised by only $\frac{3}{1000}$th part of 1° C. Professor Hill's instrument (a thermopile) could record a change in temperature which was only $\frac{1}{100,000}$th of 1° C. By means of this instrument he demonstrated that more heat was generated in a muscle after a contraction was finished than was produced during the actual stroke of contraction. This again showed that the muscular engine is contrived on very different lines from those of an internal-combustion engine, in which heat is generated and work done only during the driving stroke.

After 1909 the Cambridge workers, who were joined for a time by Dr Otto Meyerhof, now Professor of Physiology at Kiel, discovered many important things concerning the manner in which the muscles carry out the work of the human body. They discovered that at the moment when a muscle contracts, and thus does work, there is no combustion. What actually happens, then, is that a carbohydrate, either glycogen itself, or glucose, a sugar into which glycogen may be transformed, is degraded or altered to become another form of carbon compound, namely, lactic acid. This is the only chemical change—and it is not a combustion—which takes place when a muscle contracts. The more work a muscle does the greater is the amount of glycogen reduced to the form of lactic acid. All the strength we can exert by our bodies, our power to walk, to run, to jump, to swim, and to work, is obtained by the reduction of a carbohydrate from one state to another, from glycogen to lactic acid. Now, it is known that when one gram (15·43 grains) of glycogen is transformed into lactic acid, 235 calories of heat are set free. This amount of heat, if converted into mechanical energy, could lift 1 cwt. to a height of 6528 feet. It is clear that the reduction of glycogen to the state of lactic acid gives us an ample source of muscular energy.

Such is the source of energy which is expended by muscles when they contract and do work. But when it is asked how the energy thus set free by the production of lactic acid from glycogen causes the molecules which make up the substance of a muscle fibril to draw together, so that the whole fibril is shortened, we have to admit that as yet we do not know, we can only guess. Muscle or flesh is a semi-fluid substance; water makes up 75 per cent. of its volume. In this fluid substratum are suspended the particles or molecules of the muscle; they are arranged in a definite chemical pattern; they are alive; they are controlled and held in position by forces which, under certain conditions, make them attract each other, while under other conditions they are caused to repel each other. Somehow the sudden liberation of lactic acid, which is brought about in the substance of a muscle by the arrival of a nerve stimulus, causes the molecules of a muscle fibril to regroup themselves, bringing about a shortening or contraction of the fleshy, semi-fluid mass in which they are placed. The force which is expended in bringing about a regrouping of the molecules of a muscle during contraction is that which is set free by the degradation of glycogen into lactic acid. The energy which drives the engine of a motor car is derived directly from the combustion of petrol. This is clearly not the case in a muscular engine; when it contracts there is no combustion.

No sooner has a muscle reached the height of its contraction than it begins to relax; the molecules begin to resume their former positions. During relaxation the muscle gives off CO_2, and heat is generated. At first sight this would lead one to suspect that combustion takes place during relaxation, but Professor A. V. Hill has proved that such is not the case; the gas then set free was already present in the bicarbonate salts of the muscle. Carbon dioxide is set free during relaxation because the newly formed lactic acid displaces it from the salts of the muscle. We must note, however, that the production of this new salt of lactic acid—a sodium

lactate—sets free heat and energy. The degradation of one gram of glycogen into lactic acid sets free 235 calories of heat; the neutralisation of this amount of lactic acid during relaxation sets free 135 calories more; thus 1 gram of glycogen, when transformed in a muscle, gives rise altogether to 370 calories.

We have seen that a living man, like the running engine of a motor bicycle, takes in oxygen and gives out carbon dioxide; the more work each does, the more oxygen they take in and the more CO_2 they give out. The amount of combustion in each is directly proportional to the amount of work done.

We have just called attention to the most singular feature of a muscular engine—there is no combustion when it contracts and does work. When, then, does the combustion take place, the combustion which provides muscles with their source of energy? This brings us face to face with the most important discovery of the Cambridge physiologists. They found that if 100 units of heat were formed in a muscle during the act of contraction, that 150 units were given off as soon as relaxation was completed and the muscle had entered the phase of "recovery." It was during this phase of recovery that oxygen was consumed by the muscle. It was also during this phase that carbon dioxide was given off. Combustion to supply new energy took place, not when the muscle was working, but when it was at rest. What, then, is burned during the phase of recovery? What becomes of the lactic acid which is formed each time a muscle passes into action? It has been found that not all of the lactic acid is oxidised or burned. If 6 grams of lactic acid are formed during a muscular exertion, then only 1 gram is burned—is reduced to CO_2 and H_2O. The energy thus set free is used to change the other 5 grams of lactic acid back again into glycogen. Thus the muscles can use the same supply of carbohydrate again and again, by sacrificing a sixth part for reconversion. All the time, too, muscles are renewing their glycogen stock by absorbing glucose from the blood and

converting it into glycogen. For this purpose a substance formed in the pancreas, an enzyme or catalyst named *insulin*, seems to be necessary.

Thus we see that, after all, our muscles are a kind of internal-combustion engine, only the combustion takes place, not during the driving-stroke, but in the intervals which separate such strokes.

We can best imagine what kind of muscular engines our bodies are fitted out with by picturing a motor car of the following kind. Its engine does not turn the driving-shaft but is yoked to a dynamo, and the electricity thus produced is stored in an accumulator. The car is driven solely from the store of electrical energy thus accumulated. The engine is not yoked directly to the driving-shaft; all the time it is storing up energy in the accumulator. It is plain that such a car would have many advantages. Above all, it would be able to draw power from its accumulated store in emergencies—emergencies such as climbing steep hills, and others which call for great speed, such as occur in racing. Now these are just the qualities which the human machine so often requires to escape sudden danger, to win a race, or to overtake enemies.

We shall understand the merits of muscular engines all the better if we consider the human body as a racing machine. An athlete in bed or sitting comfortably in a chair will consume from 200 c.c. to 250 c.c. of oxygen per minute. As the air he breathes contains, or should contain, almost 21 per cent. of oxygen, it will be seen that he must take into the respiratory chambers of his lungs a little more than a litre of air (1·76 pints) to supply this amount of oxygen. The body at rest requires this constant supply of oxygen — 250 c.c. per minute — to supply the heart (its muscular blood-pump), the muscles of respiration (which work its air-pump), and other muscular engines, such as stomach and bowels, with the means of burning and restoring the lactic acid which each of them is continually forming.

When an athlete gets up and sets out to walk at a

pace of 3½ or 4 miles an hour, then the muscular engines of his limbs and trunk come into action. If the athlete consumed only 200 c.c. of oxygen per minute when at rest he will now need five times as much, namely, 1000 c.c., or a litre per minute. He has to breathe five times as much air as before. This he does by taking deeper and more frequent breaths. Even an untrained man can do this without feeling his exercise an effort. The blood of the walking athlete has to circulate five times as fast as when he was at rest. We shall suppose him to have 5 litres of blood in his body, each litre carrying 170 c.c. of oxygen. To supply his muscles with the necessary amount of oxygen, the left ventricle of his heart must pump blood at the rate of nearly 6 litres per minute. This the heart is easily able to do. We can also estimate the quantity of lactic acid which is being produced in his muscle as he walks at the pace just mentioned. We have seen that if 7 grams of lactic acid are produced during a muscular action, at least 1 gram of the 7 must be oxidised or burned for the reconversion of the remaining 6 grams into glycogen. For the recovery of these 6 grams 1 litre of oxygen is necessary. Therefore, if a man in walking consumes 1 litre of oxygen per minute, his muscles are producing lactic acid at the rate of 7 grams per minute, or 420 grams (16·6 ozs.) per hour. At such a pace a healthy man can walk without straining the capacity of his heart or of his lungs. They are capable of supplying his muscles with a sufficient quantity of oxygen to secure recovery of all the lactic acid produced within them. His accumulated stock of glycogen—the source of his muscular energy—is not depleted. It is possible for him to carry on at this pace for many hours without drawing upon his capital of muscular energy.

Let us suppose that such a man quickens his pace: how fast can he walk or run before he begins to draw on the stock of energy stored up in his muscles? This depends on the capacity of his heart and of his lungs. It has been found that a highly trained athlete can take air into his lungs at the rate of 25 litres per minute—

enough to supply the blood during this period with 4 litres (7 pints) of oxygen. Now, during violent exercise, each litre of blood carries only about 160 c.c. of oxygen; therefore, to carry 4 litres of oxygen round the body in one minute needs the circulation of 25 litres of blood at the rate of 25 litres per minute—just as much as an athlete's heart can do. Such a supply of oxygen is sufficient for the needs of his muscular system if this system is discharging lactic acid at a rate of 28 grams per minute. What will happen if the athlete still quickens his pace and lactic acid is produced in his muscles beyond the capacity of his oxygen supply? Professor A. V. Hill has discovered what happens. The muscles run up an oxygen debt. The amount of lactic acid which fails to be oxidised after each contraction accumulates in the muscles and then leaks into the blood; and it goes on accumulating in the muscles until it forms $\frac{1}{300}$th of their total weight; whenever it reaches this amount the muscles cease to work and the athlete drops down utterly spent. In his muscles, which we shall suppose to weigh 60 lbs., there will have accumulated 3·2 ozs. (94 grams) of lactic acid. This surplus of lactic acid has to be restored by oxidation or combustion before the muscles are fit again to work. To restore 94 grams of lactic acid needs 13·4 litres of oxygen. The muscles of the athlete during their great effort, one which lasted for the brief space of one minute, worked at a rate which was three times beyond the utmost capacity of heart and lungs to supply them with oxygen. During a special effort the athlete's muscles have incurred an oxygen debt of 13·4 litres; they need this amount to be freed of their burden of lactic acid. Hence we see why an athlete pants at the end of a fast race and rests. It will take him ten minutes' hard breathing to make good the debt his great effort has cost his muscles. But we can see the advantage of this system of oxygen credit. In primitive conditions of human life the capacity to make such sudden—almost superhuman—efforts must have saved lives on many occasions. The engines of motor cars can

do no more when they have reached the limit of respiratory capacity ; they cannot incur an oxygen debt. They stop before a debt is incurred. A muscular engine, on the other hand, when it has reached its utmost supply of oxygen, can still triple its speed, if the effort needed last but a brief time. It can do this because it can incur a heavy oxygen debt.

In these recent years we have also come to know much more concerning the efficiency of muscular engines. Methods have been devised for estimating the fuel value of the food we consume, of measuring the oxygen taken into our bodies during working and resting hours, and of registering the amount of carbon dioxide which we give off under different conditions. Exact methods have been devised of measuring the amount of mechanical work done by men and women under varied conditions. Like all machines the human body varies in its efficiency. There is an optimum rate for all kinds of muscular movement—one which yields the highest degree of efficiency. The more movements rise above the optimum rate, or the more they fall short of it, the greater becomes the consumption of food or fuel for the amount of work actually done. Movements may be clumsy or they may be apt ; clumsy and halting movements are costly. Much of the energy of muscles is lost by friction—the rubbing of muscles against each other and against their sheaths, the rubbing of ligaments against ligaments, and of articular surfaces against articular surfaces in our joints. Physiologists, after much patient observation, have come to the conclusion that a muscular system which has an efficiency of 25 per cent.—one in which 25 per cent. of the actual energy produced in it is transformed into mechanical work—is about as good as Nature can fit into a human body. In this respect the engines of the human body are no better and no worse than those which propel our motor bicycles and our motor cars.[1]

[1] Those who wish to consult recent papers on the physiology of muscles are referred to the following:—Croonian Lecture, by Sir Walter Fletcher and Sir F. Gowland Hopkins, *Proc. Roy. Soc.*, 1917, Series B, vol. lxxxix. p. 444. "Muscular Exercise," by Prof. A. V. Hill, Supplement to *Nature*, July 14,

APPENDIX C

HOW MUSCLES ARE CONTROLLED AND EDUCATED

Every year more and more is found out about these microscopic instruments which are placed in the substance of muscles and tendons for the dispatch of signals, and to which Sir Charles Sherrington has given the name of "receptors." They are the most minute of "signal-boxes." They may also be called "transmitters," for when pressed on they not only "receive" but also "transmit" messages from muscles along nerves to "nerve exchanges" placed in the spinal cord and in the brain. We have also come to know much more about the "nerve exchanges," and it is becoming very plain that the nerve exchanges of the spinal cord are very busy places when our muscles are in action—even more busy and important than those which are situated higher up in various parts of the brain itself. Sir Charles Sherrington has discovered how busy and important are these "central exchanges" or "nerve centres" of the spinal cord when we stand up and remain standing.[1] The messages which set our muscles in motion as we proceed to stand up are certainly issued from the "higher exchanges" of the brain; but when our bodies are in the standing position we are no longer aware of sending out messages to keep our muscles in action. We may stand and devote the whole of our attention to what is happening in the street or in listening to what a friend has to tell us, and yet if our friend will feel the muscles of our legs, of our thighs, of our back, and of our neck,

1923, p. 77. "The Recovery Process in Muscle," by Prof. A. V. Hill, *Lancet*, 1924, vol. ii. pp. 207, 363. "The Dynamics of Muscular Contraction," Dr H. S. Gasser and Prof. A. V. Hill, *Proc. Roy. Soc.*, 1924, Series B, vol. xcvi. p. 398. See also another paper by Prof. Hill and his assistants in the same vol., p. 438. "The Efficiency of Man," by Prof. E. P. Cathcart, *Nature*, 1922, vol. cx. p. 453. *The Human Machine*, Prof. F. S. Lee, London, 1918.

[1] See his great book *The Integrative Action of the Nervous System* (London, 1906). Readers will find a most instructive lecture by him on "Problems of Muscular Receptivity" in *Nature*, 1924, vol. cxiii. pp. 892, 929.

he will find them all in action keeping our body upright. They are being kept in action, not by the "centres" of the brain, but by those situated in the spinal cord and brain-stem. The manner in which our "standing" muscles are kept in action is simple, but nevertheless marvellous. The hundreds of muscles which keep the body erect are steadily contracting, and as they contract they press upon their "receptors" or "signal-boxes," and thus from each muscle there are passing into the "exchanges" of the spinal cord steady streams of messages.

Let us fix our attention on one muscle—that in front of the thigh—the four-headed extensor, which keeps the limb from bending at the knee if we stand with our knees slightly bent. It is connected by nerves with certain "exchanges" situated in the spinal cord. Messages are streaming from it into these exchanges. There some of them reach the nerve-cells, the "driver"-cells, which are linked to the four-headed extensor by outgoing nerves. As this muscle is constantly in action as long as we are standing, especially if our knees are slightly bent, a stream of messages is continually being transmitted from its receptors to the spinal cord. Some of these messages are "shunted" to its own driver-cells, which are thus maintained constantly in action—constantly reflecting messages which started in the muscle's own receptors. The four-headed extensor is kept automatically in action by its own messages. It is thus with all the other muscles concerned in keeping our bodies upright. From this example it will be seen that when we stand our muscles are being automatically controlled, messages are rising in them and passing to exchanges in the spinal cord. There some of them are being retransmitted as "motor" or driving messages back to the muscles from which they came; and if we assumed a standing position and had no higher exchanges in our brains which could control these lower exchanges in the spinal cord, then we should be obliged to remain standing still until our muscular engines became exhausted, and our body dropped on the ground.

Fortunately for us, through the higher centres or exchanges of our brain we can control these lower automatic exchanges of the spinal cord; we can switch them on and switch them off; we can despatch messages which alter the manner of their action. The "brain" is merely the captain on the bridge; he gives orders which start and stop his ship; the spinal centres are in the engine-room; in the intervals between orders from the bridge the engineers carry on by themselves.

Sir Charles Sherrington has also found out that the messages sent out from a contracting muscle are of different kinds. We have seen that a muscle can send up messages of a kind which causes its opponent to contract less vigorously or compels it to stop contracting altogether. Such messages can "disconnect" its opponent from the central exchange for the time being. Not only can a muscle send up messages which control its opponent, but it can ring itself off; it sends up signals of distress and stops the outflow of the messages from the spinal exchange, which keep its fibres in a state of contraction. It can switch itself off and thus pass into a state of rest. John Hunter, the great surgeon, observed that this happened in the muscles of the calf of his leg when he ruptured their tendon (the tendo Achilles) by dancing too vigorously.

Certain physiologists in Holland have found out another very wonderful thing concerning the control of muscles. In our heads—connected with deep parts of our ears—are placed a pair of the most delicate balancing instruments imaginable[1]; and yet they are very small and really simple in their construction, for each is filled with fluid, and on their floor rise up microscopic hairs or cilia, on the tips of which rest minute chalk-stones or otoliths. When we bend our heads forward, the otoliths tend also to fall forward, thus bending the cilia on which they rest. If we bend our head sideways, then the otoliths fall in an equal degree towards the same side and press upon the cilia on which they rest.

[1] The labyrinth and semi-circular canals of the internal ear.

Now, the cilia are "receptors"—living mechanisms for receiving and transmitting nerve messages. As they bend under the movements caused by their otoliths, messages stream out along their nerves to a great central exchange placed on the stem to the brain. From there the stream of messages is distributed to the multitude of nerve-centres or exchanges which control the muscles of the body, particularly those which maintain the body in a standing position. All of us have been spun round upon a swing until, when we jumped down, we could no longer stand; we had become giddy and lost all control of our standing muscles. The exchanges in the spinal cord which control these muscles had, when we were being spun round, been bombarded by a hurricane of messages issuing from the balancing instruments in our heads, and had thus thrown out of action for a time the exchanges which control the muscles used in standing. The movements of a ship upset us in a similar way, until the centres which control our muscles become accustomed to them and learn to neglect them.

Messages which issue from the balancing instruments in the head control many of our movements. A dog will live without a brain. Under chloroform its cerebrum may be excised and such a dog will recover. It will eat and drink when food and water are given it, but it has no will; it can issue no orders to the muscles which can raise its body up into a standing position. But if such a dog is placed in the standing position it will remain in this posture, for all the control centres of the spinal cord come automatically into action. Dr Magnus of Utrecht discovered that if the head of such a dog were moved so as to imitate the natural motions of the head in the act of rising, the muscles of the neck came into action, and so also did the muscles which place the forelegs in their just position needed for this act. By carrying out further passive movements of the head, Dr Magnus was able to set in motion all the muscles concerned in rising. By other movements of the head this animal was made to assume the characteristic attitude of a seated

dog, gazing fixedly at a shelf fixed to a wall in front of it. Dr Magnus discovered that the messages which brought about such attitudes issued from the balancing instruments of the head. From such experiments we learn how wonderfully the animal body is made. But we also learn a much more important lesson; the brain itself—the organ of our will—has, after all, only a limited power over our muscles. But man has a greater conscious power over them than any other animal; more than any other animal he can "educate" his muscles.

In these lectures I have spoken as if the brain could obtain complete control of the muscles of the body and become a perfect "engine-driver." It is well for us to set out in life believing this to be the case. Yet we do know that when a child is born, the muscles which are used in sucking and the "central exchanges" which control them, are all in order—all are already educated and fit for work. It is so with the muscles of respiration; afterwards the brain can control the muscles we use in breathing to a certain extent; we may make some of them work more and others less, and really modify the nerve exchanges which control them. A newly born calf will rise and walk, all its nerve-centres are already trained. We have to learn to walk, but we do this by setting in operation the exchanges which are already established in our spinal cords. The brain does not deal directly with muscles; it can only influence their manner of action by obtaining a dominion over the automatic exchanges or nerve-centres of the spinal cord.

The longer we live the more do we realise the importance of the lower centres which control muscular action—the centres in the spinal cord and brain-stem. Almost every boy is ambitious to excel in sport—in speed of foot, in jumping, in cricket, and football; nearly every young man wishes to become a scratch player at golf. But, try as we will, the greater number of us do not succeed in rising above an average standard. That we have not succeeded in rising is not for want of trying. Success in all forms of manual skill and in all forms of

sport which demand the utmost precision in the use of muscles, depends on the proficiency of the lower exchanges of our nervous system—the centres of the spinal cord and brain-stem. If we are born with these centres aptly and effectively fitted out, then it is easy for the higher centres in our brains to improve them; but if they are less efficiently endowed by Nature, then we can hardly hope to raise them above mediocrity. The nervous system with which a child is born is a Pandora's box packed with gifts of varying degrees of excellence. If some are bad, others are likely to be good. The game of life lies in making the best of what we have, and that can be done only by education.

APPENDIX D

CAN CARTILAGE CELLS BECOME BONE-BUILDERS?

The reader will observe that I speak of the colony of bone cells in the epiphysis at the lower end of the femur as if it were composed of immigrants which had made their way from the surface of the epiphysis to its interior, bringing with them a supply of blood-vessels. This was the opinion held by most anatomists when these lectures were given; they believed that all bone cells appeared first on the surface of the cartilaginous bones of embryos and therefore when bone cells were found in the heart of a piece of cartilage they were regarded as having emigrated from the surface.

More careful inquiry is now showing that this opinion is not well founded. Lately Dr C. W. Stump[1] of Edinburgh has studied the first appearance of the bone-builders in the lower epiphysis or cartilage of the femur of developing children. He has examined the very earliest stages and found that there was then no penetrating leash of blood-vessels and no evident track by which the colony of bone-builders could have made its

[1] *Journal of Anatomy*, 1925, vol. lix. p. 136.

way from the surface of the cartilage to the interior. Further, a close study of the members of the early colony showed him that they were really cartilage cells which had become changed; from being cartilage-builders they had become bone-builders. It is when the colony undergoes this change of trade that the blood-vessels on the surface send in a penetrating leash, carrying to a growing colony an increased supply of nourishment. We do not know what causes a few cartilage cells in the interior of an epiphysis to become thus suddenly altered in nature; the change occurs at approximately the same date in the growth of every child, but some day we shall find out the manner in which the change is brought about. We do know, however, many instances where blood-vessels send out a newly-formed leash of channels. In the transparent cornea or window of the eye, there are no blood-vessels. But if an ulcer should form on the cornea, then from the vessels at its margin there will grow out a leash of vessels which penetrates to the ulcer and carries nourishment for its healing. The cartilage which lines our joints has no blood-vessels, but let disease break out, or a fragment of the cartilage be injured, then there will shoot out from the network of vessels round the margin of the cartilage a leash of new vessels and this leash will reach the point of injury and supply the nourishment needed for active repair. We do not know how the injured part makes its needs known, nor how the surrounding vessels are stimulated to come to the rescue; we simply know that such things do occur and that the way they are done can be found out if we will but inquire.

We must, therefore, give up the idea that when an embryonic cell has become a cartilage-builder it can never again change its trade. Cartilage cells, under certain conditions, can become bone-builders. We have known for a long time that there are occasions when bone cells become turned into cartilage cells. This may happen when a bone is broken. The bone-builders, which are exposed on the fractured surface, are stimulated, multiply,

change their shape as they increase in number and undertake the work of repair. Many of them, as they multiply, become cartilage cells. We have every reason to suppose that, as the fracture mends, they again become changed into bone cells. Thus the castes of bone-builder and cartilage-builder are not absolutely fixed; under certain conditions they can be interchanged. What the anatomist wishes to find out are the exact conditions which bring about the alteration, because, if he knew, he might be able to produce such changes in the growing child—when Nature's attempts have failed.

APPENDIX E

THE NOURISHMENT OF CARTILAGE

Investigations recently made in the Royal College of Surgeons, England, by Mr A. T. G. Fisher, throw a new light on the manner in which the lining cartilage of our joints is nourished. He took a small fragment of living cartilage and placed it within the joint of a living animal, so that it was bathed by the synovial fluid of the joint. After some months he examined the implanted piece of cartilage and found that it was still alive and had greatly increased in size. We must infer, therefore, that it had imbibed nourishment from the synovial fluid of the joint. Synovia is thus more than a lubricant; it can also supply the cartilage which lines our joints with nourishment. We conclude on this evidence that articular cartilage may draw its supply from two sources—the network of fine vessels which lie in the bed of bone under it and from the synovial fluid which lubricates its surface.

Loose pieces of cartilage are occasionally formed in the knee and other joints of men and women and have to be removed by surgeons because they sometimes become caught between moving surfaces, thus giving rise to sudden and severe pain. Mr Fisher's investigations throw light on the origin of such cartilages. Either as

the result of an accident, or because of disease, a small fragment of the lining cartilage is broken off; it drops into the synovia of the joint and, drawing its nourishment from this fluid, is able not only to remain alive, but also to grow, and attain a large size. We must remember that such pieces of cartilage are no longer exposed to the constant wear to which normal cartilage is exposed, and hence they may attain a considerable thickness.

In my text I have written as if the villi or processes of the synovial membrane which project into a joint were concerned only in the draining off or absorption of fluid; it is highly probable that they also take a share in the formation or secretion of the lubricating fluid.

APPENDIX F

THE OUTPUT OF THE HEART

Harvey's estimate of the amount of blood pumped by the left ventricle into the arteries is a moderate one. His calculation, stated in the metric system, is 1·988 litres (70 ozs.), in round numbers, 2 litres a minute. In recent years—as has been already mentioned in Appendix B—physiologists have employed an accurate and simple way of calculating the output of the heart during life. A litre of arterial blood, when fully laden, carries slightly more than one-fifth of its volume of oxygen—namely, 210 c.c. A man at rest, if of average size, will consume about 250 c.c. of oxygen; 1·25 litres of blood will absorb and carry this amount. The left ventricle of a resting man pumps blood at the rate of 1¼ litres per minute—¾ of a litre less than in Harvey's estimate. But if such a man sets out to walk at a rate of 4 miles per hour he will consume 1 litre of oxygen per minute—five times the amount required when at rest. To carry this amount of oxygen to the tissues his left ventricle has to pump five times as much as before, namely, at a rate of 6¼ litres

per minute. Harvey's estimate of 2 litres per minute would thus apply to a man taking very gentle exercise.

It is instructive to compare Harvey's estimate with one which Professor A. V. Hill made recently on an athlete who, during violent exercise, consumed oxygen at the rate of 5·9 litres per minute. Each litre of blood, if fully saturated, carried 210 c.c. of oxygen. To carry 5·9 litres of blood under these conditions requires 28 litres of blood. The left ventricle, to supply this amount of blood to the muscles of the athlete, must pump at a rate of 28 litres per minute. Under such circumstances Professor Hill believes that each litre of blood will carry only about 160 c.c. of oxygen and that, therefore, in this athlete the left ventricle must have pumped blood into the aorta at the rate of 37½ litres per minute. The right ventricle had to pump at a similar rate and, therefore, the total output of this athlete's heart was at a rate of 75 litres per minute—about 17 gallons, or 120 times the heart's own volume. Records were kept of the rate at which the athlete's heart worked; it was beating 180 to the minute. Therefore at each beat the left ventricle forced into the aorta 200 c.c. of blood. Harvey modestly estimated each output as 1 oz.; in Professor Hill's athlete it was 7 ozs. "It is little wonder," adds Professor Hill, "that the heart sometimes cannot stand the strain."

Professor Hill [1] also estimated the amount of work done by the heart of this athlete during the extreme effort just alluded to, and the amount of oxygen consumed by the heart itself. His calculation shows that the heart was consuming oxygen at the rate of 200 c.c. per minute—almost as much as is used up in a similar period by the body of a man at rest. To supply this amount of oxygen to the heart of the athlete, 2 litres of blood must be pumped per minute through the coronary arteries—the vessels which carry oxygen and nourishment to the heart's musculature. No wonder the coronary arteries are liable to disease; they are subjected at times to enormous strains.

[1] *Lancet*, 1924, vol. ii. p. 364.

The reader will observe that in the text the total amount of blood in an average man's body is stated to be 5 litres, while in the appendices 7 litres is sometimes given as the amount. Both figures are right; the amount of blood varies from person to person, depending on the size of the body and many other circumstances, but the lower figure is nearer a just average.

APPENDIX G

BREATHING, THINKING, AND HEALTH

In these lectures the manner in which breathing is carried on in the human body is compared with a corresponding process of an internal combustion engine. The comparison holds for conditions such as we find at no great height above sea-level. It will repay us to study them at great altitudes above the level of the sea where a full supply of oxygen for combustion is more difficult to obtain. Let us suppose we have the fortune to accompany an airman who is to ascend and fly, as many of them did during war time, at an altitude of 18,000 feet (3·4 miles). We shall encounter great cold, but we may presume that care has been taken to protect both engine and passengers against it. As we take flight from the aerodrome, situated at the bottom of the great sea of air in which we live and breathe, we notice that the barometer registers a pressure equal to 760 mm. of mercury (29·9 inches), but as we ascend we notice that it steadily falls until, at a height of 18,000 feet, it registers only 380 mm.—half of what it did at the aerodrome which now lies nearly 3½ miles beneath us. At this great height—and we are still 11,000 feet below the level of the crest of Mount Everest, the air has the same composition as below. If we take a litre of it we shall find, in round numbers, that 79 parts are nitrogen and 21 parts oxygen. But if we burn a candle in this litre of air for half an hour we shall see that the oxygen is

sufficient to burn only half the amount consumed at the aerodrome in the same time. It is the same with the combustion of petrol; the engine of the aeroplane has a fixed size of lung—its cylinder; it cannot take bigger and quicker breaths. So as the air becomes thinner the amount of petrol or fuel admitted to the cylinder is decreased in amount. This is done automatically by a mechanism worked from a barometer. As the aeroplane reaches a height of 18,000 feet, the petrol supply is reduced to half, and the speed of flight is correspondingly diminished. Under those conditions, how does respiration go on in the body of the aviator and in the lungs and muscles of we who accompany him? In him as in us oxygen has to be carried by the blood from the lungs to the tissues where combustion takes place; in such a high altitude as we have reached the machinery of conveyance is apt to break down. This is not likely to happen to the aviator, for he is a tried man, and has already been tested for living at high altitudes. Very likely our respiratory system will fail us, unless we be among the fortunate ones with a highly adaptable mode of breathing. If we are observant we shall notice, as we reach a height of 12,000 feet or 14,000 feet, that our hearing becomes less acute, our sight somewhat blurred, and our mental perception sluggish. We may become emotional and be moved to laughter or to tears. A headache comes on and a sense of lassitude creeps over our bodies; the condition known as "mountain sickness" develops. If we try to do ever so simple a sum, we do it over and over again and do it wrong every time. Clearly at the height of 18,000 feet we are not in a condition to discuss what has happened to our respiratory system; we must wait until we return to land. As we descend towards the earth and again reach the bottom of the sea of air in which we live, our senses begin to do their offices again—and our brain to pursue its usual avocations with clearness.

It is worth making such an ascent were it only to learn how much clear thinking depends on an ample supply

of oxygen to the nerve cells of the brain. Nerve cells are more easily suffocated than any other units of the body, particularly those which have to do with consciousness and thought. It was not necessary, however, to take so arduous a flight to learn this lesson, for physiologists, by experiments carried out in their laboratories in recent years, have produced and studied all the breathing and mental disorders of high altitudes.

To understand what they have already found out, and what they are now discovering, we must note what happens to the oxygen of the air from the time it enters our lungs until it has reached the tissues of the body—heart, glands, brain, muscles—where it is consumed or burned. It becomes particularly important to observe the "partial pressure" or head of pressure exerted by oxygen at each stage of its transit from the time that it enters our lungs until it reaches our tissues. Oxygen forms 21 per cent. of the air we breathe; its partial pressure is therefore 21 per cent. of the weight of the atmosphere. The weight of the atmosphere at sea-level is 760 mm.; the partial pressure of oxygen is $\frac{21}{100}$ of 760 mm. = 160 mm. of mercury. By the time the breath has mixed with the air in the terminal saccules of the lungs, the percentage of oxygen has been reduced to 13 per cent. and therefore its partial pressure—its power of diffusion through the wall of the saccule into the blood—has become reduced to $\frac{13}{100} \times 760$ mm. = 98·8 mm. of mercury. Owing to the moisture in the contained air of the lungs we have to make a further reduction—the actual pressure of the intra-saccular oxygen being only 90 mm. Hg. The large drop in the percentage of oxygen in the saccules is due to its mixture with 5·5 per cent. of carbon dioxide, the product of combustion, thrown out from the venous blood into the saccules. The proportion of CO_2 in the air of the saccules is maintained steadily at or near 5·5 per cent.; this percentage is maintained because by the mechanism already described (p. 143) the rate and depth of breathing are thus automatically regulated. It is important to take notice of the partial

pressure of CO_2 within the saccules; it is $\frac{5\cdot5}{100}$ of 760 mm.=41·8 mm., but here, too, we must make a reduction to 40 mm. on account of moisture present. If CO_2 is to make its way by diffusion from the venous blood into the air saccules of the lungs, it must have a partial pressure—a power of diffusion—above 40 mm. Hg.

Let us look for a moment at the manner in which the oxygen is conveyed from the lungs to the tissues. It is carried by the red blood corpuscles; there are 250 billions of them engaged in this trade in the blood of an average man. If we learn what one corpuscle does we shall know what all the others do. We shall pick our corpuscle as it enters a capillary in the wall of a saccule of the lung, on its return from the tissues. It is in a venous state; when fully laden with oxygen it has absorbed an amount equal to a fifth of its own volume. As it enters the wall of the saccule it is not empty of oxygen; it still retains about 60 parts of its full load. It proceeds at once to load up from the oxygen diffusing through the moist wall of the air sac, but as a rule it does not quite complete its full load of a hundred parts; by the time it has reached about 95 parts it is hurried away on another journey to the tissues. The oxygen in the air saccules of the lungs, from which the red corpuscles are charged, has a partial pressure of 90 mm.; the corpuscle thus carries a load of oxygen at the same pressure—with a power of diffusion nearly equal to 90 mm.

We follow this laden corpuscle as it makes its swift journey through the arteries to enter a capillary lying alongside of a muscle fibre. This fibre is actively at work and in need of oxygen for the combustion of its discharge of lactic acid. The oxygen tension in such a muscle fibre is very low; in the corpuscle it is high, and so the oxygen quickly diffuses from the corpuscle to the fibre. By the time it has parted with 40 per cent. of its load, the corpuscle has been hurried from its capillary and carried along in the venous stream until it again reaches the lungs to take up another burden. If the tension of oxygen in the working fibre of a muscle is low,

it is otherwise with its charge of carbonic dioxide—the product of lactic acid combustion. Hence, as oxygen diffuses from the corpuscles of arterial blood into the muscle cylinders, carbon dioxide diffuses from the cylinders into the blood. The arterial blood reaches a muscle fibre charged with CO_2 at a tension or partial pressure equal to 40 mm. Hg, the exchange from the muscle cylinder has increased this charge; in venous blood CO_2 has a partial pressure of about 47 mm. Hg, 7 mm. above that of arterial blood. About half of the charge of CO_2 is carried in the red corpuscles and half in the plasma in which the red corpuscles are floating. On arrival at the lungs the venous blood, with its charge of CO_2 at 47 mm., is exposed to the intra-saccular air in which the CO_2 is maintained at a tension of 40 mm. Hence the surplus burden of CO_2 gathered from the tissues is discharged into the lung. Respiration, which is so simple in the internal-combustion engine, is a complicated process in the human body.

Such is the machinery by which oxygen is conveyed to the tissues of the human body under ordinary conditions. Why does this machinery break down—temporarily at least—when we ascend to high altitudes? We need not go to mountain tops to study the reasons; "high altitudes" can be produced in physiological laboratories. The one we propose to visit first is that of Dr John S. Haldane of Oxford, who has done more than any living man to unravel the mechanism of respiration. Just after the war, Dr Alex. Kellas, a distinguished chemist and expert mountaineer, went to Oxford to join Dr Haldane in an experiment. They wished to experience the atmospheric conditions which were to meet the brave men who had determined to reach the summit of Mount Everest.[1] They entered an air-tight steel chamber to which an exhaust pump was attached, taking with them instruments and note-books to record the observations they were to make on each other.

[1] Dr Kellas was a member of the first Mount Everest Expedition. To the sorrow of his companion he fell ill and died during the ascent.

Having shut themselves in, they turned on the exhaust pump; the pressure of air in the chamber at once began to fall. They experienced the conditions which meet every aviator as an ascent is made. They allowed the chamber to be exhausted until their barometer had sunk almost to 300 mm., corresponding to an altitude of 25,000 feet. At this pressure Dr Kellas, although his lips had become blue, was still able to make observations, sluggishly and with a sense of great effort. Dr Haldane became dazed and handed his note-book to Dr Kellas. At this low pressure, or high altitude, they remained for about an hour, Dr Kellas continuing to make entries and all the time putting questions to Dr Haldane, from whom he received the same monotonous answer whatever the question. Both had really become stupid, particularly Dr Haldane, and yet he was then most confident that he was in full possession of all his faculties, which shows that the more stupid we are, the less we recognise our state. When Dr Kellas re-admitted air until the pressure was equal to an altitude of 16,000 feet, he observed that Dr Haldane, when he took up a hand-mirror to note the complexion of his own lips, used the back of the mirror for this purpose. After air had been gradually admitted, bringing Dr Haldane back to a full use of his senses, he found he had no recollection of what had happened after handing his note-book to Dr Kellas. Brain cells need a full supply of oxygen if they are to serve as the registers of memory.

Now, when we remember that a man at complete rest needs a supply of only 250 c.c. of oxygen per minute to keep his tissues provided, and that, in great efforts, his lungs can supply him with fifteen times this amount, we are at first puzzled to give an explanation of the condition into which Dr Haldane passed. When the atmospheric pressure in the chamber went down to 300 mm., each breath still contained 40 per cent. of the normal amount of oxygen and therefore it might be thought, by taking breaths which were 2½ times larger than usual, or by taking breath at 2½ times the normal rate, a full supply

of oxygen would be brought into the lungs. Now to quicken his breathing is just what a man tends to do when he ascends to high altitudes. So long as the air contains about 60 per cent. of the normal amount of oxygen, he encounters little difficulty in his breathing, but, when it falls below this amount, when he ascends above 13,000 feet, he finds that his respiration becomes disturbed. He feels a need to breathe deeper and quicker, thus increasing the circulation of air in the saccules of his lungs. Unfortunately, his attempts, while they bring more oxygen into these saccules, also wash out and carry away from them their due content of CO_2. He thus deprives himself of his respiratory "governor." The amount of CO_2 in the pulmonary saccules (normally it is kept at 5·5 per cent. with a partial pressure of 40 mm.) regulates the amount of CO_2 in the blood; the amount of CO_2 in the blood is the chief factor in regulating the nerve centres which control breathing. Hence the attempts to obtain more oxygen has the effect of removing from the blood the very substance which urges the respiratory centres to increased action. Thus the respiratory centres of a man who ascends into high altitudes is deluded into a sense of false security by the absence of its normal stimulus—an absence of a surplus of CO_2 in the blood. Give these centres time, and they will become accustomed to the new conditions. "Mountain sickness" is not unlike sea sickness; one is due to a disturbance of the centres which control breathing, the other to a disturbance of the centres which control our equilibrium.

Much, as we have seen, can be learned about breathing in high altitudes by experiments carried out in physiological laboratories; more still can be learned by studying men, women, and children who spend their lives in a rarefied atmosphere, such as is to be found in communities on the plateau of the Peruvian Andes. There, people live at an altitude of between 14,000 and 15,000 feet. In the winter of 1921–1922 a company of physiologists went to study one of these communities, and also to note the changes which took place in their own bodies

as they passed from sea-level to the plateau. The observations made by this expedition have been compiled and published by its leader, Dr Joseph Barcroft of Cambridge.[1] On arriving at Cerro, situated on the Peruvian plateau, 14,200 feet above sea-level, they suffered, some to a greater degree and some to a lesser, all the physical and mental disturbances already mentioned. Their lips and complexion became more or less plum-coloured, showing that their blood did not carry its usual charge of oxygen. The natives on the plateau were more dusky than those that lived at sea-level, and they had larger chests. All kinds of work on the plateau—mental and physical—were found to give a greater sense of effort; it became more difficult to fix the attention—to concentrate on the task in hand; every kind of toil required to be broken by frequent rests; a tendency to impatience and to irritability required constant watchfulness.

Our interest in the members of this expedition lies in the behaviour of their lungs and blood. They found that their hearts, although they beat more quickly, pumped about the same amount of blood in a given time at Cerro, 14,200 feet up, as at sea-level. The volume of air they breathed per minute underwent only a slight increase. Dr Barcroft, for example, who took 6·8 litres of air per minute into his lungs at sea-level, increased this amount at Cerro to only 7 litres. At Cerro the barometer stands at 460 mm., therefore each breath he took had only 60 per cent. of that contained in a breath at sea-level. He expected to find that the oxygen in the saccules of his lungs would be present in a proportion to give it a pressure of 38 mm.; what he did find was that oxygen was present in his lungs in a higher proportion than he had anticipated; it stood at a partial pressure of 48·4 mm.—which was 10·4 mm. above his expectation. This was due to increased filling of the lungs—the increased filling is part of the acclimatisation process. It lowers the amount of CO_2 in the lungs, and thus increases

[1] *Phil. Trans. Roy. Soc.*, 1923, vol. ccxi. (B), pp. 351-480.

the proportion and partial pressure of the contained oxygen. A fall in the pressure of the oxygen in Dr Barcroft's lungs, from 103 mm. at sea-level to less than half of this amount at Cerro, must have hindered the loading of his red blood corpuscles. When these appeared in the capillaries of his lungs, although travelling at their usual rate, each corpuscle was found to pick up only about 85 per cent. of its usual load of oxygen. To carry the usual supply of oxygen to the tissues the corpuscles would have had to move faster and be increased in number. During his stay at Cerro, Dr Barcroft's red corpuscles underwent an increase of 30 per cent. Many of the natives of Cerro had an increase of 50 per cent. of red blood corpuscles above what occurred in natives at sea-level. An increase of red blood corpuscles with their *hæmoglobin* is another of the means by which the human body is acclimatised to high altitudes.

At high altitudes the regulated discharge of CO_2 is upset. At sea-level the percentage of this gas in the saccules of Dr Barcroft's lungs was maintained at 5·2 per cent., with a partial pressure of 39·3 mm. Hg. The nerve-centre which regulates his breathing is set so as to work round this standard. At Cerro the percentage of CO_2 in his lungs had fallen to 4·3 per cent. with a partial pressure of 31·5 mm. Its amount had diminished under increased ventilation, and his venous blood would therefore part with a larger proportion of its CO_2 than at sea-level. At Cerro he found that the CO_2 in his venous blood was diminished by 25 per cent., and we should expect it, therefore, to be less acid in its reaction and thus less of a stimulant to his respiratory centre. In spite of the diminished percentage of CO_2 in his blood, its reaction was found to be not less, but rather more, acid than before. Evidently some other substance with an acid reaction had made its appearance in the blood as substitute for the missing volume of CO_2. Here, too, we seem to have another factor in the acclimatisation of human beings to high altitudes.

The degree to which the respiratory system of man can

be adapted for life at high altitudes is illustrated by the experience of the Mount Everest Expedition of 1924. Four members of the party reached a height of 28,000 feet—3000 feet above the atmospheric level which took away all faculties of mind and body from Dr Haldane. Dr Haldane sat passively while these men had to climb—had to supply their muscles with the large supply of oxygen demanded by their muscular engines. At such altitudes their red blood corpuscles could carry only a fourth or less of the supply of oxygen needed for combustion in their muscles and to keep the nerve-cells of their brains in action. No wonder that each step upwards cost them a Herculean effort. It was at a height of 28,000 feet that Mr G. L. Mallory and Mr A. C. Irvine were last seen—with their faces turned towards the face of Mount Everest, and only a thousand more feet to conquer. It was not given to them—if they conquered—to return alive. One thing we may be certain of, the end came to them in the most merciful of forms; their brains and feelings were benumbed, as in the deepest of sleep, long before cold death spread through their limbs. Those who have studied the conquest of Mount Everest most closely believe that the way to the top lies through acclimatisation, the acclimatisation of climbers who have shown that their respiratory systems have a special aptitude for life at high altitudes.

In war time many aviators, particularly those who had to ascend and to fight at great heights, suffered from a condition known as "flying stress." Brave men lost their nerve; many became neurasthenic. War alone is enough to break down the nerve-control of resolute men, but flying men had not only to endure the exigencies of war, but also the ordeal inflicted by changes in altitude. In "flying stress" the regulation of the respiratory system breaks down because it is called upon to do so much under abnormal conditions. Group Captain Martin Flack[1] has studied the respiratory condition of men

[1] "The Milroy Lectures on Respiratory Efficiency in Relation to Health and Disease," *Lancet*, 1921, vol. ii. pp. 593, 637, 693, 741.

who suffer from flying stress, and also worked out a method of discovering recruits who are unfit for flying owing to the mode of their breathing. In normal pilots the lungs contain sufficient oxygen to keep the needs of the body supplied for a minute or more; hence, such men can hold their breath for 60 or 70 seconds, while in sufferers from flying stress, and in those men who are unfit to become pilots, the hold breaks down in 50 seconds, or in even a shorter period. The lungs of such men contain less than the normal supply of oxygen, and their respiratory centres are unstable and less under control of the will. Captain Flack found out, too, that the capacity of such men to empty their lungs had undergone a curious change. This relates to the amount of residual air—the air in the lungs which cannot be forced out on expiration. In a normal man this should amount to about 1000 c.c., but in those suffering from flying stress the residual air rises to 1500 c.c., or even 2000 c.c. They have lost the power of emptying their lungs to a normal degree. There is a reduction also of 500 c.c. or 1000 c.c. in the extra air which can be taken in after a normal breath has been taken. Their vital capacity has been reduced. Their range of useful breathing has been diminished at both ends. The range to which the lung can be emptied and filled is curtailed both above and below, with the result that such men suffer from a condition similar to that which occurs at high altitudes. There is the same lack of oxygen supply and the same kind of impairment in the action of the brain. The condition of "flying stress" may overtake men and women who have never flown or lived at high elevations. A curtailment in the range of breathing may overtake those who live sedentary or soft lives. With a defective supply of oxygen to the body there sets in a train of nerve disturbances to which medical men give the name of neurasthenia. Defective breathing is not the sole nor even the commonest cause of neurasthenia, yet there is much to be said for the treatment of such cases by breathing exercises. The most natural way of setting the lungs in motion is by

exercise—sharp walks or five minutes' use of dumb-bells.

What is the volume of a normal breath? Physiologists give half a litre, 500 c.c. (30 cubic inches) as the amount taken by an average man taking twelve breaths per minute. That this is a just estimate for men in good condition there can be no doubt. Dr Rushton Parker has called my attention to the fact that in many people, particularly people who lead a quiet, sedentary existence, the usual breath is less than half the amount given above—only about 15 cubic inches or 250 c.c. of air. Such breaths are sufficient to meet the needs of a body at rest—to supply a system which is consuming oxygen at the rate of 250 c.c. per minute. If we breathe at the rate of twelve per minute, taking 250 c.c. at each breath, then we take air into our lungs at the rate of 3000 c.c. per minute, 620 c.c. of it being oxygen. Of the 3000 c.c. of air thus taken in we have to remember that only about 70 per cent. of it reaches the saccules of the lung, but this amount will still hold 434 c.c. of oxygen, which is well above the 250 c.c. demanded by the body at rest. When we speak of half a litre as the volume of a normal breath, we are referring to men in full health.

APPENDIX H

VITAMINS

Although it is quite true that the ultimate value of any kind of food we eat depends upon the amount of heat or energy it gives off when burned, yet we have come to know in recent years that what we eat must contain bodies which have no value as producers of heat and yet are essential for the maintenance of health. These *accessory food substances* are now known as vitamins —a name which was given to them by Dr Funk in 1913. They are present in such excessively minute quantities

that the chemist has not been able to isolate them in a pure state, and yet the physiologists can detect their presence by the action they produce on living bodies. If vitamins are added to a rat's daily diet in an amount which does not exceed even a $\frac{1}{35,000}$th of a grain, the animal will absorb and utilise its food; it will remain in health. If this trace is withheld the animal will waste and ultimately die. If it be a young and growing animal, growth will cease. We know from medical experience that the same is true of human beings; certain vitamins, or *advitants* as Prof. H. E. Armstrong has named them, must be present in food if children are to grow and adults are to be healthy. In this respect living machines differ altogether from those made of metal.

How medical men came to know of the existence of vitamins makes a very interesting story. I can remember very well how ignorant we were of them in the year 1892. I was then in Siam, and part of my duties was to look after the health of Chinese coolies, many of whom suffered from a strange disease known as beri-beri. It was a serious disease; many coolies died of it. Medical men practising in the Far East were searching for its cause and its cure; and we all searched in vain until Dr C. Eijkman, a physician in Java, showed us that the cause and cure lay under our very noses. Between 1892 and 1897 he had many opportunities of proving that it was when coolies were fed on white, polished rice, particularly if the rice had been stored for some time, that beri-beri broke out amongst them. Men who were fed on unpolished rice—husked rice which still retained its brown coating and germ—did not suffer. He cured men who suffered from the disease by simply adding rice "polishings" to their dietary. Thus it was made evident that beri-beri was a disease of the same order as scurvy. Early navigators knew that they could quickly cure sufferers from this disorder by feeding them on fresh vegetables or fruits.

Looking back now it seems strange that no one jumped at the true significance of such discoveries as these. No

one did until 1912, when Sir Frederick G. Hopkins of Cambridge proved that a health-sustaining diet always contained minute traces of *accessory substances.* No matter how well a diet answered the chemical needs of the body, it failed to maintain animals in health if these accessory substances had been extracted and withheld; the same dietary became efficient the moment a trace of accessory substances was added. As we have seen, the accessory substances discovered by Sir Frederick Hopkins were given the name of vitamins by Dr Funk in 1913. Two years later Drs M'Collum and Davis of Baltimore were able to separate and distinguish one kind of vitamin from another. They found that one kind of vitamin is soluble in fat, and was therefore present only in foods which contained fatty substances. They found it in the fat of mutton and of beef; it is present in cream, butter, and whole milk. This vitamin, which they named Vitamin A, is particularly abundant in cod liver oil. Vitamin A proved essential for growing animals; if it is withheld, growth slows down and ultimately ceases. Long ago medical men had found out by experience that cod liver oil was the best medicine for rickets, but they did not know why it cured until Vitamin A was discovered.

Unlike Vitamin A, Vitamin B is soluble in water; it should be present in bread. Yeast-cells contain a considerable trace of it; it, too, is essential for health and growth. A third vitamin, Vitamin C, makes up the present list, but there are probably many more yet to be discovered. All three are present in whole, unskimmed milk. Vitamin C is particularly abundant in germinating seeds; it is the absence of this vitamin which gives rise to diseases such as beri-beri and scurvy.

How can substances which are present in the most minute quantities bring about such far-reaching, almost magical effects? In Chapters XVIII. and XIX. mention is made of substances known as ferments or enzymes, which are formed in the stomach and bowel, and play a very important rôle in the processes of digestion.

They are present in amounts so small that they cannot be separated in a pure state, and yet when they have done their work they seem to remain undiminished in amount and unchanged in structure. In another chapter (XXI.), we shall meet other substances of a like nature known as *hormones*; minute traces of them bring about changes in the action and growth of various organs of the body. The only bodies which act in a manner at all comparable to vitamins, enzymes, and hormones, are those which chemists name catalysts. When jets of oxygen and hydrogen are made to impinge on a mass of spongy platinum they break into flame and form water. The platinum is unchanged; it acts as a catalyst, causing the atoms of hydrogen and oxygen to combine. Sulphuric acid, added to starch, causes the starch to become a sugar (glucose), and yet the acid remains unchanged. The acid acts as a catalyst. Vitamins, enzymes, and hormones, seem to act in the living body as catalysts. The more we come to know of the physiology of the human body, the more we see that catalytic substances play an all-pervading rôle in its economy. We have every reason for supposing that there are numbers of such substances remaining yet to be discovered and investigated in man's body.

Chemists discovered the existence of catalytic action little more than a century ago. Nature discovered and used it at her first attempt to fashion organised life. The human body cannot manufacture vitamins; no animal body can, so far as we yet know. Plants can and do manufacture them for their own use. Vitamin A is present in every green leaf; there it may serve as catalyst for the upbuilding of starch and other substances under the influence of light. Vitamin C is particularly abundant in sprouting seeds; it serves as a catalyst in the upbuilding of the new tissues of the growing plant. Wherever we find a bud there, too, we find vitamins, for they are essential for growth. Vitamin A abounds in the oil extracted from the liver of the cod. The cod did not manufacture it, but obtained it from the bodies

of small crustaceans on which it feeds. The small crustaceans did not manufacture it, they obtained it from the diatoms on which they feed. Diatoms are members of the vegetable kingdom, and are manufacturers of Vitamin A. Thus we cure a rickety child suffering from a lack of Vitamin A by giving him a catalyst which had served the turn of many and varied members of the animal kingdom before it reached the puny child of the palace or the suffering urchin of the slum. Herein we see how economical Nature is in all her enterprises. She wastes nothing. When she builds higher forms of beings she utilises to the full the resources already assembled in the evolution of lower forms. When animals were evolved to feed on living plants and seeds, she used the catalysts which they had produced for their own use to serve the needs of the beasts which came to eat off them. Man is no better in this respect than other members of the animal kingdom. He is dependent for his supply of vitamins on the cast-off catalysts which have done duty in blades of grass, grains of wheat, as well as in bodies of the humble sheep and cow.

APPENDIX J

THE ORIGIN OF PETROLEUM, THE HEAT VALUES OF FOOD, AND THE WORK-EFFICIENCY OF THE HUMAN BODY

The statement that petrol may be derived from the liver of sharks and of other fishes is apt to excite incredulity. A full statement of the evidence for this opinion has recently been published in book form by Professor John Muirhead Macfarlane (*Fishes—the Source of Petroleum*, 1922). The geological strata in which mineral oils occur are those which were laid down at periods when inland waters were swarming with many kinds of fish, particularly those of the shark family. "The group of fishes alone in the animal kingdom,"

writes Professor Macfarlane, "conforms in every respect to the requirements for the formation of crude petroleum." In the shark's body, as in man's, the carbohydrate, glycogen, is the fuel used in muscles. It is stored in the liver and conveyed by the circulation from there to the muscles, being transformed into a sugar, glucose, for the purposes of transit. Hence it is quite possible that the glycogen stored up by a shark some 15 million years ago, to serve as fuel for its muscles when in pursuit of prey, may now be carrying a modern motor car forwards on its journey.

The origin of petroleum is not definitely solved, but nearly all authorities agree that it has been derived from living matter of past geological epochs. It is more probable that it arose from dead animals than from dead plants, and of the various kinds of animals which could give origin to it, fishes are the most likely. Professor A. Maihle of Toulouse has prepared a synthetic petrol from linseed oil.

On p. 160 I have made the statement that, of the total energy which a working man takes in as food, he gives out only 12 per cent. as mechanical work. This, no doubt, may seem a very low estimate, and yet it does represent what is accomplished by an average labourer. Professor E. F. Cathcart, our leading authority on this matter, found a gross efficiency of 17·6 per cent. in a cyclist on whom he made measurements. As the man under observation became tired, his efficiency fell to 16·1 per cent. In every kind of mechanical task there is an optimum rate at which work should be done to obtain a maximum efficiency; if the task is performed above this rate, or below it, there is a fall in efficiency—in the proportion of energy consumed to output in work.

Physiologists study the human body as an effective work-machine exactly as engineers study an engine. Both employ the same unit for making their calculations, namely the calorie. The calorie is, as we have seen (Appendix B), the amount of heat required to raise one cubic centimetre of water from 15° to 16° C.

This amount of heat, when converted into mechanical work, is sufficient to lift one kilogram (2·2 lbs.) 427 metres high. Such a calorie is too small a unit for comparing the work of large machines, hence, in the study of the human body, as of engines, the *large* calorie is adopted. The large calorie is the amount of heat required to raise 1000 c.c. of water (one litre) from 15° to 16° C., one thousand small calories being thus equal to one large calorie.

When a litre of ordinary petrol[1] is consumed in the cylinder of an internal-combustion engine it gives off 7500 calories, of which 30 per cent. (2250 calories) is converted into mechanical work. An engine which produces work to this amount on a litre (1·76 pints) of petrol is said to have an efficiency of 30 per cent. A horse, dragging a moderate load, expends 642 calories per hour on work. Therefore, if a horse could use petrol as a food or fuel at an efficiency of 30 per cent., a litre of petrol would supply its needs for 3½ working hours. If a man could obtain his energy from the consumption of petrol, then a litre of it, when digested, absorbed, and oxidised, would supply his needs for 18 working hours, for the muscles of a horse can do as much mechanical work of a simple kind in 1 hour as those of a man can do in 5·4 hours. It takes fully five men to haul a horse's load. The fuel used in muscular engines is glycogen. When an ounce of it is burned or consumed it gives out 108 calories of heat, whereas an ounce of petrol gives out nearly twice as much—namely 202 calories. Some constituents of our food, however, such as fat or butter, have a higher heat-value and energy-value than petrol. When an ounce of fat is fully burned in the human body it gives out energy to the value of 263 calories—which may be used in the heating of the body or may be turned into mechanical work. Proteins derived from flesh, fowl, or fish have also a high content of energy ; an ounce of protein, when burned, gives out 150 calories. Cane sugar gives off 112

[1] The author is greatly indebted to Prof. W. E. Dalby, F.R.S., of the Imperial College of Science, for help in this section.

calories for each ounce burned ; glucose, which is really a hydrated form of glycogen, gives off only 108 calories.

There are several ways by which we may find out the efficiency of the human body as a work-machine. We may place a man inside a heat-tight chamber, a greatly magnified vacuum flask, and measure the total amount of heat given off by his body—(1) when he is at rest ; (2) when doing light, moderate, or hard work. Or we may do it in a simpler way. All the energy manifested in a man's body, the movements of his trunk, limbs, heart, and intestines, as well as the secretory and other activities of his tissues, is contained in the food he has eaten. If, then, we know the amount of solid food actually absorbed from his intestines and consumed by his tissues in a given time and know the heat value of each item in his dietary, then we can estimate the calories of heat which have been set free in his body during that time. There are still two other ways. All the energy set free in our bodies comes ultimately from combustion or oxidation. If we measure the amount of oxygen consumed by a man at rest over a definite period, we can estimate the number of calories set free in that time. Or we may measure the amount of CO_2—a product of combustion—which a man gives off from his body in a given time and in this way get at the amount of energy transformed.

In recent years physiologists have employed one of these methods or a combination of them to find out how much energy, stated as calories of heat, is needed by a man when he keeps his body at rest, and how much is required under various conditions of work. Professor Cathcart found that a man of average size—with a body surface or skin area of 30 square feet—burned the fuel in his body at a rate of 1700 large calories per 24 hours. It needed this amount of energy to keep his heart and other organs at work when he was doing no mechanical work. One ounce of cane sugar yields 112 calories when completely burned ; therefore, by consuming a little over 15·1 ozs. of sugar, a resting man could obtain sufficient energy to supply the needs of his body for a

period of 24 hours. In a corresponding period an average woman would require the equivalent of 1580 calories, which she could obtain from 14 ozs. of sugar. If we set our average man to a sedentary occupation for a period of 8 hours in the 24, then his output of energy is raised 400 calories above his resting requirement. To meet this extra expenditure we should have to raise his resting allowance of sugar, 15·1 ozs., to 18·7 ozs. —an increase of 3·6 ozs. to cover the cost of the energy expended in doing work. As a work-machine he expends 400 of the 2100 calories consumed in performing external work. But, when this external work is measured, it is found to have the equivalent of about 80 calories; therefore only about 80 calories of the 2100 produced have been converted into effective work. The gross efficiency of his body as a work-machine is only 3·8 per cent. If we put him to light work, the expenditure of calories rises 700 above his resting number, and hence we have to raise his sugar allowance from 15 ozs. to 21·4 ozs. to meet his increased output of energy. His efficiency as a work-machine thus rises to 7·3 per cent. If asked to do moderate work, his increase of calories becomes 1000 above his resting output; he requires an allowance of 24·1 ozs. of sugar to meet his needs. His efficiency as a work-machine rises to 9·2 per cent. If we put him to heavy work, then his output of calories may rise 2000 above the resting expenditure. To supply him with sufficient fuel and energy we must raise his allowance of sugar to 33 ozs., which is 18 ozs. above his resting allowance. We have raised, at the same time, his efficiency as a work-machine to 13·5 per cent. If, however, we do not take into account the 1700 calories consumed merely to keep his body in existence during the 24 hours in which this spell of work was done, then his efficiency—net efficiency—rises to 25 per cent. From actual observation, Professor Cathcart[1] found that a man doing work of a known mechanical value had a *net* efficiency of 23·3 per cent. If man's body is viewed

[1] "The Efficiency of Man," *Lancet*, 1922, vol. ii. p. 547.

merely as a work-engine and rated on a strictly commercial basis, then its gross efficiency, ranging from 10 to 14 per cent., stands far below engines which man employs as sources of power. These range from 20 to 30 per cent. in their gross efficiency. We need not think less of ourselves because of this inferiority; after all, man's body is much more than a commercial source of mechanical energy. By his brain he is opening up and bringing under control untold sources of energy.

APPENDIX K

THE EFFECTS OF CIVILISATION ON MAN'S BODY

The liability of our teeth to decay is only a small part of a great problem which is occupying the attention of medical men at the present time. When we compare the bones of men now living in England with those of long past generations we find many points of difference. Decayed teeth are much more common in us than they were in our predecessors of a few centuries ago. The jaws of our forefathers were more regularly and more stoutly framed than ours. Contractions of the palate, giving the external appearance of "rabbit mouth" so common amongst us, are never seen among the earlier men of England. The shape of the orbits and the general contour of the modern face have changed in a large number of our present population. It would be impossible for a short-sighted hunter to procure a supply of food for himself and family, and yet amongst us there are 150 individuals in every thousand who cannot see things clearly at a distance. We must infer that some change is at work in the eyes of many living families. It is difficult to believe that many ailments of our digestive system were so prevalent in olden times as they are now. Various disorders of the great bowel, grouped under the name of intestinal stasis, diseases of the appendix, of the duodenum, and of the stomach are so

common amongst us that we must conclude that these organs are more liable to disorder and to disease than they were in former times. It is difficult to believe that insanity, neurasthenia, and other disorders of the nervous system were as common among our hunting forefathers as they are to-day.

The reader will have observed that in the text of this book I have ascribed the liability of our teeth to decay to a lack of use and of attention. At the present moment I have before me the jaws and teeth from an early Saxon cemetery in England. Scarcely a tooth is affected with caries, although they are coated with tartar, showing that the Saxon invaders of England were negligent of dental cleanliness. And some of these teeth, although they have been on active service in the mouths of men and women for over twenty or thirty years, are yet remarkably little worn. With such facts before me it has become increasingly difficult to believe that the liability of our teeth to decay, and of our jaws to be imperfectly shaped, and of our bowels to become the seat of disorder, is due simply to disuse. It seems more probable that our maltreatment of them goes deeper than mere disuse.

A fuller knowledge of our history shows us that we, the natives of North-West Europe, have effected a revolution in our manner of living in a comparatively short period of time. Five or six thousand years ago our forefathers, few in numbers, lived in temporary shelters in the open country, where they were exposed to all changes of weather. They gathered a scant subsistence from the roots, fruit, fish, and game of their native localities. And now we are massed together in cities, in thousands and in hundreds of thousands, living on a strange artificial dietary and sheltered by well-built houses and warm clothing. In a short space of time, on the evolutionist scale of reckoning, we have transformed the conditions of life; we have placed the human body in a new environment and are only now awakening to the fact that we have embarked on a great experiment —one so complex that its issues are difficult to forecast.

At first we attempted to explain such bodily changes as were forced on our attention by adopting the simplest and more plausible explanation possible. We thought that our teeth became liable to decay because we had so altered our dietary that there was no need to use them for grinding down our food. Teeth were certainly evolved for this purpose, and, not being dead but very living things, they cannot maintain their structure and density if not fully used. Disuse, therefore, may be a factor in their liability to caries, but it is not the only one. Another alleged factor is a lack of cleanliness. Another cause is said to be the over-use of sweet or of starchy foods. In more recent years the inquiries of Dr and Mrs Mellanby have revealed another and more potent factor. They found that if certain elements which are contained in fresh foods—vitamins—were withheld when teeth are being formed in the gums, then such teeth are imperfect in their texture and are liable to decay. With the knowledge of this discovery and of others of a like kind, our outlook has broadened; we begin to realise that our modern dietary may affect the sound development and growth, not only of teeth, but of other structures in a pernicious manner. The susceptibility to such disorders of growth is certainly much greater in some families than in others. We are thus led to see that susceptibility is a matter which has to be taken into account. We have to discover the full meaning of susceptibility and of immunity, and the manner in which Nature produces these two states which are the opposite of each other. Could we find this out, then we might discover a way of removing the susceptibility and replacing it by an immunity. In this way we have been led to see that the evil condition of our teeth is not a simple affair of disuse. The liability of our teeth to decay has become part of a great general problem, namely, the kind of reaction which our bodies are making to the new conditions in which our modern civilisation has placed them.

The vermiform appendix attached to our great bowel is liable to disease; in many of us, after we have passed

adolescence, this small structure becomes reduced in size, its lumen closes and the muscle of its wall changes to fibrous tissue: it atrophies. It is said to atrophy and become liable to disease because it has ceased to be useful. By way of reproach, it is called a vestigial structure. Now the appendix is never vestigial in a newly born child ; we have every reason to think that it is as well developed in the newly born child of to-day as it was in children born 10,000 years ago, or even a million of years ago, for it is scarcely larger in a newly born anthropoid ape than in a newly born child.

The great bowel itself has been called a useless structure ; it could hardly be called vestigial by anyone who has actually noted its large size. The great biologist, Elie Metchnikoff, was of opinion that man would be improved if he were born without a great bowel. Many modern surgeons, sharing his belief, excise it when it is so seriously disordered that a patient is better without it than with it. But no surgeon would dare affirm that a person without a great bowel had a modicum of the health enjoyed by those who have big bowels of even indifferent efficiency. Metchnikoff said, very justly, that many parts of our bodies are imperfectly adapted to the lives which we have now to lead. Well, it is not Nature but we who have chosen most of these conditions ; they are of man's making, not of Nature's. We expect our digestive systems to deal with artificial dietaries which we now thrust upon them just as effectively as with natural foods, for which they were originally fashioned. They have to digest and absorb substances very unlike those which the ancestral great bowel had to manipulate. We must have patience with the digestive tracts which have come down to us, and study their past history and their present capabilities if we are to succeed in humouring them into doing the new kinds of office we have thrust upon them. We can hardly expect Nature to speed up her machinery of adaptation and so fashion our bodies that we may run riot amongst the tempting luxuries which modern civilisation has

placed within our reach. The way out of the evils which seem to threaten us is not to lay the cause of failure at Nature's door, but to see how we can accommodate the benefits of civilisation to the capabilities of the bodies she has given us.

APPENDIX L

INSULIN AND HORMONES

We have seen that the carbohydrates, destined to serve as the fuel of the body, are stored in the liver as glycogen. From the liver this store of fuel is gradually set free in the circulating blood as a form of sugar (glucose), and this is carried to muscles and to other tissues throughout the body to be oxidised or consumed by them, according to their requirements. Only a small amount of sugar is present in the blood at any given time. The blood of an average man contains only about ¼ oz.; it is dissolved in the total blood of the body, which amounts to 176 ozs. (5 litres). The sugar present in the blood thus forms 15 to 25 parts in every 10,000 parts of the blood. If the proportion rises above this, especially if over 40 parts or more, then an overflow of sugar sets in; it escapes by the kidneys into the urine. This happens sometimes in men and women, not because they eat too much sugar, but because their muscles and tissues cannot utilise the supply in their blood although present in only a normal amount. The sugar fuel, so sorely needed by their muscles, nerve cells, and other tissues, runs to waste in their urine. The machinery necessary for the combustion of carbohydrates (of glycogen and of glucose), has broken down in such men and women; they suffer from the disease known as *Diabetes*.

The cause of this breakdown we did not know until 1922. Early in that year it was proved to be due to the absence of a hormone formed by the pancreas, one to which the name *insulin* was given. Dr F. G. Banting, a

young Canadian medical practitioner, took the leading part in this discovery. Certain ideas occurred to him while in the practice of his profession. He had been thinking over what was known about diabetes. He was well aware that so long ago as 1889 two physiologists, von Mehring and Minkovski, had excised the pancreas from living dogs, and had thus produced diabetes in them. They proved, too, that diabetes would disappear if a piece of pancreas were grafted into any part of the body of a dog in which such an operation had been done. Dr Banting was also well aware of the fact that the pancreas contained, scattered throughout its substance, little islands of cells—the islands of Langerhans—which were known to have nothing to do with the formation of pancreatic juice, but were suspected of producing a substance—an internal secretion—which escaped into the circulating blood. No one had ever succeeded in extracting or isolating this internal secretion. Dr Banting suspected that the reason of this failure was owing to the fact that those who had sought to extract the substance had chopped up the whole gland—mixing the islands and their secretion with the parts which are concerned in the formation of pancreatic juice, which is digestive in its action. The secretion of the islands would thus, he suspected, be digested and destroyed. So he thought of a method by which the secretion of the islands could be protected. He remembered a fact which was well known to physiologists, namely, that the juice-secreting part of the pancreas slowly degenerated and disappeared when the main duct of the gland was tied in a living animal, but the islands still remained healthy and intact. He therefore supposed that if a pancreas which had atrophied from having its duct tied were chopped up, then the secretion of the islands would escape destruction by digestion and could thus be isolated and used for purposes of experiment.

Dr Banting gave up his practice and went to the Physiological Laboratory of Toronto University, where Professor J. J. R. Macleod gave him every encouragement.

He was joined by Dr C. H. Best, and later by Mr Collip, for the experiments he set out upon demanded an extensive and intimate knowledge of physiological chemistry. He quickly found that he had guessed rightly: from the duct-tied pancreas he succeeded in extracting a substance which, when injected into the veins of a diabetic rabbit, caused the sugar to disappear from its urine and from its blood. Then a way was found of extracting this substance from the pancreas or sweetbread of calves and of slaughtered animals so that it might be used freely for medicinal purposes. The essential ingredient of such extracts was found to be a hormone to which, as I have already mentioned, the name insulin was given.

The right size of dose needed in the treatment of patients—men, women, and children—suffering from diabetes, was worked out, and injected into their veins with marvellous results. Their symptoms disappeared; they could again eat and drink the ordinary things of life; their strength at once began to return; sugar no longer flowed to waste in their urine. There was, however, one serious drawback. A dose, given by a hypodermic injection, lasted only a few hours and was required at least twice a day. The need for continued injections will be realised by anyone who is familiar with the manner in which the glands of internal secretion work. Glands such as the thyroid, pituitary, adrenal, and pancreas, which produce hormones, are constantly at work. They eject their peculiar products into the circulating blood at the right times and in the most minute doses. Medical men cannot reproduce in the bodies of their patients a carefully adjusted mechanism of this kind. The best they can do is to copy Nature's method as nearly as possible by injecting into the blood of the sufferer two doses of insulin daily. The patient is dependent on these two doses; if they are withheld, disease resumes its sway and death ensues more or less quickly. Clearly, insulin is only a palliative for diabetes; the real cure must be the discovery of how the pancreas can be safeguarded against the disease which leads to the destruction of its insulin-

producing parts. In this, as in so many diseases, prevention proves to be the only cure.

The discovery made by Drs Banting and Best revealed the immediate cause of diabetes and placed in the hands of medical men—not a cure—but the means of alleviating the condition of those who suffer from a most distressing disease. The discovery of insulin, however, did much more than this ; it threw a new light on the machinery of combustion in the bodies of man and beast. The highly complex nature of the machinery became apparent to all. Insulin is needed for the storage of the carbohydrates in the liver ; when these substances are absorbed from the food they are transformed into glycogen in the liver, insulin being necessary for this process. Somehow the organs concerned in digestion can call forth from the pancreas supplies of insulin in the proportion needed to deal with the amount of carbohydrates absorbed. We have seen that muscles, when in action, need large supplies of carbohydrates to serve as fuel. They have the means of calling forth stores from the liver, of imbibing and incorporating these stores as parts of their living contractile substance. How they call them forth we do not know, but insulin is necessary before the supplies in the blood can be assimilated and utilised by the muscles. If insulin is withheld, the carbohydrates run to waste in the urine. Nerve cells need a constant supply of carbohydrates. If too large a dose of insulin is given to a patient, then the sugar quickly begins to disappear from the blood, and when it sinks from the normal amount—15 parts in 10,000—to 4 parts in 10,000 of blood, then the nerve cells of the brain and spinal cord begin to pass into an excitable state. Unless the sugar supply is replenished in the blood, as the patient can do by eating a few lumps of sugar, a state of extreme distress sets in, followed by convulsions and death. Insulin must be added to the blood in the exact dose which meets the needs of the nervous system. We have seen that oxygen is needed for the right working of our brain cells ; we now see that they need a regulated supply of glucose

to serve as their fuel. The nerve cells which give us consciousness, which is the power to feel, think, see, and hear, must be provided with a constant supply of materials for combustion—oxygen and sugar. These two are useless unless insulin accompanies them to serve as a catalyst or uniter.

Secretions thrown into the circulation by the adrenal gland, thyroid and pituitary, can also influence the rate of sugar combustion in the body. We have seen that sugar is normally present in the ratio of 15 or 20 parts to 10,000 parts of blood. Above these proportions the sugar begins to overflow from the kidneys. But in a certain disease of the pituitary gland the amount of sugar in the blood may rise to 40 or 50 parts in 10,000 of blood, or even to higher proportion. A condition of sugar tolerance is induced by an overaction on the part of the hinder lobe of the pituitary gland. For this gland, besides secreting substances which control growth, also forms others which control the amount of sugar circulating in the blood. It may throw out an excess of this hormone. Men and women who suffer from this form of sugar tolerance become fat because their tissues have an excess of fuel at their disposal. Usually, too, their sexual glands undergo an atrophic change.

We see then how complex the processes of combustion are in the human body. In an internal-combustion engine oxygen is mixed with petrol vapour; a spark ignites this mixture; the machinery of combustion is of a simple kind. Why this process should be so complex in the human machine is explained in Appendices B and J. One other fact impresses us. We have seen that the kinds of vitamins which serve the purposes of the lowest animals are the same as those which answer the needs of the highest. It is the same with hormones; the same insulin that serves the needs of the rat, rabbit, or calf, will produce the similar effects when it circulates in the human body.

APPENDIX M

THE HUMAN BODY AS A SOCIETY OF MICROSCOPIC UNITS

Throughout the first twenty chapters I have treated the human body as if it were a single machine. Up to the year 1839 medical men always wrote and spoke of man's body in this way; for them it was a single organisation compounded out of various kinds of living tissues. After 1839 it was no longer possible for them to look on it in this simple manner. At this date the microscope became sufficiently powerful to reveal the secret structure of the tissues which form the body. Skin, bone, hair, nails, nerves, muscles, and brain were, one after the other, shown to be made up of minute living units or cells closely set together in hordes or masses. Bit by bit it was demonstrated that the billions of units which make up a child's body were the progeny of a single living unit—the fertilised egg. By division after division the living fertilised ovum of the mother gave rise to the immense progeny of units which make up the body of her child. Then the microscope revealed the fact that the waters of sea, lake, river, and pool were swarming with living units—bacteria and germs of endless kinds. These units were found to remain separate from birth to death; they lived in swarms, and the individuals of a crowd might be social up to a point. The units which issued from a fertilised ovum did not separate; they remained clubbed together; as division went on and their numbers increased, they became so closely knit together that they seemed to form but a single individual to the unaided eye. Without the microscope we could never have guessed that the huge population of a child's body was the progeny of a single microscopic parent—the fertilised ovum.

Then a further truth became apparent. It was found possible to trace every stage between the lowest stage, where living units remain separate all through life as in the amœbæ of our ponds, up to the highest stage,

where in the body of a dragonfly or of a human being billions of units are so closely knit together that they appear to form—and in reality do form—a single individual. Then in 1859 came Charles Darwin, who compelled all thinking biologists to believe that the minute single-celled forms of life were the first and oldest, and that the highest forms had been evolved from the lowest by a process of aggregation and specialisation of living units.

The first man to perceive clearly that we must regard the higher plants and animals as "societies" of living units was Herbert Spencer. In 1846, when he was twenty-six years of age, he began to search for an ideal government to serve the needs of living peoples. He desired to find out the rules which men and women must obey if they would live together happily, prosperously, and economically as members of a community or of a country. We need not trouble about the rules which he ultimately proposed for the right regulation of a society or commonwealth of human beings. It is enough for us to remember that at the time he began to think about these matters, biologists, with the aid of their microscopes, were making the discoveries which I have mentioned above. In 1851 he became familiar with the fact that the body of a living animal, such as that of a man, was made up of an untold number of units, and that these units were the assembled family of a single unit. He therefore began to question biologists and to search their writings for information about the regulations or government which made such societies, as that represented by the human body, a possibility. He hoped to obtain hints from the biologists which would help him to frame rules for the government of human societies. The more he studied the bodies of animals the more he was convinced that they were huge and successful societies of living units. But he soon found that biologists had nothing to teach politicians. On the other hand, he found that he, a student of human societies, had many fruitful suggestions to make to

biologists. For our highest human society represents but a low stage in the scale of nature's societies as represented by the bodies of higher animals. As so often happens when a new idea is given a premature application, Spencer's conception of an animal's body as a society met with little acceptance. It was not until the present century was four years old that the discovery of hormones —substances which regulate the conduct of living units —compelled biologists to consider again Spencer's conception. We have come by a more accurate knowledge of the kinds of rules which keep the billions of living units of the human body acting in unison so as to give the impression that it forms a single, self-regulating machine.

Men who know nothing of Spencer are again running their minds over the facts which convinced him, and as they review these facts, and others which have been added since Spencer's time, they, too, come to the same conclusion—that the human body is a gigantic but uncommonly well-governed community or society. It is only when we come to regard the human body in this light that we can interpret the discoveries which medical men are ever making—discoveries relating to immunity, to susceptibility, to malignancy, to errors and disorders of growth, and to the number of hormones and their rôle. My friend Mr Morley Roberts, independently of Spencer's writings, arrived at the society conception of the animal body, and has elaborated this conception and applied it to the explanation of malignancy—to the onset of cancer and sarcoma.[1]

We see, too, that not all the units of the human body have lost their power of locomotion. White blood corpuscles move in the blood and in the tissues with the same facility as does the ancient amœba. Many kinds of cells can, under certain conditions, cease to be " fixed " and again become wanderers, just as staid town-dwellers may become the inhabitants of travelling caravans. The male sperm still retains a method of movement which

[1] *Warfare in the Human Body*, London, 1921.

was practised by simple organisms in earliest unicellular times. We cannot fathom the complexity nor understand the efficiency of the human body unless we regard it as an immense and most highly-organised society of living microscopic units. We have just begun to find out how this society is controlled, ruled, and governed. When its government is fully unravelled we shall have presented to us, not ten, but ten thousand different forms of regulating substances or hormones.[1]

APPENDIX N

AUTOMATIC NERVE EXCHANGE

In 1923 the British Post Office decided to adopt automatic devices in all large central telephone exchanges to perform the work then done by living "operators." The automatic system is already widely used in the United States of America.[2] In this system a subscriber no longer "calls up" an operator in his exchange and asks to be "put through" to another subscriber—perhaps one of 15,000, with whom he wishes to communicate. Instead of "calling up," the subscriber manipulates a dial, causing it to indicate the number with which he wants to be linked. As he moves the indicator he is at the same time manipulating an automatic "operator" placed in his central exchange. When I say he "manipulates" a central operator, I mean only that he controls or guides it, for the energy which gives the central mechanism a power of motion is obtained from an electric battery installed in the central exchange.

Thus as the means of telephonic communication improve, we see that the direction of evolution follows

[1] Readers will find this idea more fully elaborated in a paper contributed by the author to the *Rationalist Press Association Annual*, 1924, p. 3.

[2] For an account of "Automatic Telephones," see F. A. Ellson's *Automatic Telephones* (London, 1924).

that taken in the building up of a nerve system in the bodies of living animals. For the essence of the system which prevails in the human body is the control which "subscribers" exercise over the "operator" in the central exchanges. These exchanges of our nervous systems are automatic. Somehow the miniature "signal-boxes," "receptors" or "transmitters," which we find in every particle of our bodies, have the power of directing the messages they dispatch through exchanges of the nerve system to their right destination. It happens not infrequently that when we ring up a mundane exchange that the operator replies often somewhat brusquely, "Number engaged." This, too, happens in the new automatic exchanges, and the mechanical operator, in this case, promptly and politely, returns a "block signal" to the caller. In the automatic nerve exchanges similar conditions hold; a message is refused if the outgoing line is engaged. In physiological language, the message is "inhibited." In one respect the arrangements in a nerve exchange are superior to those in an automatic telephone system. No matter how urgent the subscriber's message may be, he has to wait until the desired number is free. But in a nerve exchange a really urgent call has precedence; it can disconnect the original caller and take his place. Clearly such a system as this would be unworkable in our modern exchanges where the majority of subscribers believe that their particular time is the most precious and their messages the most urgent. In a polite society, such as we find in the animal body, there is less danger of the privilege of "urgency" being abused.

The installation of an automatic system in a local exchange presents the telephone engineer with problems which he can solve easily. Our difficulties begin when we connect local or parish exchanges with the larger exchanges in the town of their district; they increase as we link up these district exchanges with that in their county town, and they grow almost insuperable when we have to link up all the county exchanges with the great central or

Westminster exchange, wherein the government departments are installed. If a parish subscriber dispatches a message to a government department, his message has to set going not only the automatic mechanism in the local exchange, but also those of the more elaborate installations at district and county centres before it reaches its final destination at Westminster. This actually happens in the exchanges which are installed with such profusion and in such complexity in the central nervous system of man's body. Messages are automatically transmitted through exchange after exchange, year in and year out, with scarcely a blunder. In Great Britain, to-day, there is a population of 47 millions, but only a million are telephone subscribers. In the human body, with a population which has to be counted in billions, the vast majority are subscribers and their calls are incessant. It is only when we use such a simile as this that we come to realise the vastness and intricacy and efficiency of the system which has been installed in the body of a human being to carry out its immense and continuous traffic in nerve messages.

To make this conception of a nerve system better understood, let us take a concrete example. A typist sits at her machine with her eyes turned on my confused manuscript, her fingers busily engaged on the keyboard, turning my sheets into neatly typed pages. She has set going in her brain and spinal cord a most elaborate series of exchanges where steady streams of nerve messages are being switched and shunted without cessation and without error. The messages are being taken up from my manuscript by the retinæ of her eyes, sensitive films in which are set an infinite number of microscopic rods and cones. These rods and cones are the receptors or transmitters of light signals; every one of these retinal transmitters is linked by a nerve fibre to a great exchange situated in the brain. This first, vast exchange, with its tens of thousands of retinal subscribers, is situated, not in the occipital cortex where retinal pictures rise up into consciousness, but in the base of the brain. It is situated here for a good

reason. We notice that, as the typist reads, her eyes move along the lines of the manuscript. Her eyes are moved in unison by six pairs of muscles. The exchanges which work and control the movements of the eyes have to be constantly informed of what is happening in the retinæ, and hence the first optic exchange is situated at the base of the brain near those which control the movements of the eyes. The eyes have to be kept constantly in focus; the amount of light admitted to the eyes has to be constantly regulated by the action of the iris; the exchanges which control these actions are also near the first optic exchange. We notice, too, that her head has not only to be poised, but turned, as sentence after sentence is read from the manuscript. The exchanges which control head movements are also linked up with the first optic exchange. The automatic management of the eyes thus involves a series of subsidiary exchanges controlled from the basal or main optic exchange. The optic exchange in the base of the brain is linked up by great nerve tracts with extensive exchanges situated in the occipital cortex of the brain. In these exchanges the retinal messages are transmuted into visual pictures; in neighbouring exchanges the pictures are registered and interpreted. From these exchanges messages are automatically transmitted to centres in "motor areas" of the brain—areas which contain the dominant exchanges—exchanges which control the lower basal and spinal centres which regulate movements of fingers, arms, and shoulders. To permit the arms to work with a free and precise movement, the body has to be kept upright and steady, so as to provide a firm basis from which the shoulders, arms, and hand can work. In the typist's body over one hundred muscular engines are being turned on and off, speeded up and again retarded as she sets the keys of her machine in motion. These lower centres are largely automatic or self-controlled; the brain only sets them going; it can speed them up, slow them down, switch them off, or alter their mode of action. Every muscle is constantly sending up to its own spinal exchange a stream of messages and as

constantly receiving a stream back again. It is when we begin to disentangle the processes involved by such an everyday action as that of typewriting that we begin to realise the marvellous complexity and efficiency of the organisation of the human nervous system.

INDEX

Abdominal viscera, movements of, 131.
Absorption, 189.
from great bowel, 215.
from small bowel, 204, 205.
Accessory food substances, 308.
Achilles, tendon of, 15, 61, 289.
Achondroplasia, 74.
Acromegaly, 227.
Adhesions, formation of, 88.
Adrenal glands, 118, 224, 229.
Afferent nerves, 246.
Air, composition of, 123, 297.
Air-content of lungs, 140, 307.
Air-hunger, 162.
Air sacs of lungs, 120, 139.
Alcohol, absorption of, 189.
Alimentary canal, length of, 164.
musculature of, 172.
obstruction of, 179.
system, 159.
system of motor cycle and human body compared, 161.
transport mechanism, 164, 171, 178.
workshops, 164.
Alveoli of lungs, 140.
Amylopsin, 197.
Anger and other passions, 118.
Animal spirits, 243.
Ankle-joint, 83, 87.
Anthropoid apes, 239.
Anthropoids, forearm of, 66.
Aorta, 93, 112.
Appendicitis, 213.
Appendix vermiformis, 191, 195, 213, 319.
Appetite, 163.
Arch of foot, 16.
Architecture of bone, 75.
Arteries of muscles, as inlet pipes, 29.
pressure in, 108, 112.
stopcock mechanism of, 115.
use of, 93.
Articular surfaces, 82.
Asphyxia (see Suffocation).
Assimilation (see Absorption).
Association areas, 239, 332.
Astragalus or ankle-bone, 82.
Athletes as "engine-drivers," 40, 291.
overheated muscles in, 34.
Atlas vertebra, 25, 50.
Auricles of heart, 100, 109.
Automatic telephone exchanges, 255, 329.
Automaton driver, 232.
Axis, use of, 55.
Axis-cylinder, 249.

Backbone as fulcrum of ribs, 127.
mechanism of, 21.
Bacterial digestion, 210.
Balance of muscles, 128.
Balancing, 232.
apparatus, 289.
of backbone, 23.
of body in walking, 19.
Ball-and-socket joint, 52.
Ball-bearings, lubricant as, 80.
repair of, 270.
Banting, Dr F. G., 322.
Barclay, Dr A. E., 209.
Barcroft, Dr Joseph, 304.
Battery, compared to nerve cell, 256.
Bayliss and Starling, 178, 199.
Bell, Sir Charles, 245.
Bellows of human machine, 132.
Beri-beri, 309.
Best, Dr C. H., 323.
Biceps of blacksmith, 227.
structure of, 28.
Bile duct, 201.
formation of, 201.
Bismuth test-meal, 170, 195, 207.
Black, Dr Joseph, discoveries by, 123, 148.
Blood, amount pumped by heart, 105, 295.
change of colour in, 148.
combustion mixture in, 29.
concoction of, 91.
corpuscles, white, 230.
effect of heating, 156.
pressure, maintenance of, 109, 113.
reaction of, 143, 305.
sugar in, 321.
total amount in body, 114, 297.
Bomb-dropping, effect of, 118.
Bone, architecture of, 77.
Bone-builders, 69, 167, 273, 292.
Bone corpuscles as architects, 75
as undertakers, 79.

Bone, death of, 79.
growth of, 72.
nature of, 47, 292.
remodelling of, 70, 77.
repair of fracture, 73, 272.
structure of, 69.
Bones as levers, 47.
Bowel, great, area of, 213.
construction of, 211.
excision of, 320.
excretion from, 215.
functions of, 214.
movements of, 207.
retrograde nature of, 216, 320.
transport system of, 202, 212, 218.
of motor cycle, 196.
small, 194.
area of absorbing surface, 208.
as shoddy mill, 198.
influenced by nerve system, 204.
microscopic structure of, 205.
mucous membrane of, 199.
muscle coats of, 172.
obstruction of, 203.
Boyle, Hon. Robert 147.
Brachial muscles, 41.
Brachialis anticus, 64.
Brain as a machine, 232, 287.
as General Headquarters, 221.
as telephone system, 244, 329.
blood supply of, 117, 241.
connections with spinal cord, 259.
discovery of functions, 243.
discovery of structure, 244.
education of, 291.
effects of heat on, 157.
its higher manifestations, 235.
mechanism of, 262.
of battleship, 252.
organisation of, 264, 329.
size of, 235.
Brain-stem, 52, 237.
Brake-action of muscles, 18.
Breast-bone, 125.
Breathing (see Respiration).
Breathlessness, 271, 297.
Bronchi, 136.
Bronchial, musculature, 137.
Bronchioles, 137.
Buffer-properties of foot, 63.
Buffers formed by cartilage, 84.
of spine, 22.
Bulloch, Prof. W., 230.
Buttock, muscles of, 17.

Cæcum, 195, 209, 320.
as a dump-head, 206.
structure of, 212.
Calf of leg, 62.
"Call of nature," 218.
Calorie, definition of, 277.
Cancer, nature of, 275, 328.
Candle experiments, 148.
Cannon, Prof. W. B., 117, 162, 184, 225.
Capillaries, discovery of, 105.
of lungs, 142.
Capillaries of muscles, 36.
Capillary fields, 106, 108, 156.
Carbohydrate foods, 188, 314.
Carbon dioxide, 123, 142, 278, 281, 299.
as hormone, 143, 223, 303.
as product of combustion, 281, 315.
discovery of, 148.
partial pressure of, 301, 305.
Carburettor, 11.
as absorbing system, 160.
Caries of teeth, 167, 319.
Cartilage at ends of bones, 72.
builders, life-history of, 72, 85, 293.
nourishment of, 84, 294.
of joints, 82.
of ribs, 125.
Castration, effects of, 229.
Catalytic action, 341.
Cathcart, Prof. E. F., 287, 315.
Caval veins, 91.
Cavendish, Hon. Henry, 149.
Cell doctrine, 231, 249, 274, 326.
Cells, societies of, 327.
Cells (see also Corpuscles).
Cellulose, digestion of, 210, 217.
Centres of ossification, 72, 292.
Cerebellum, 193, 237, 263.
Cerebral hemispheres, 237.
Cerebro-spinal fluid, 235.
Charge stroke, 12.
Chest (see Thorax).
Chinaman, heel of, 59.
Christmas dinner, digestion of, 184.
lectures, preparation for, 4.
Chyme, 194, 197.
rate of passage of, 196.
Ciliary action in trachea, 138.
Ciliated epithelium, 138.
Circulation, discovery of, 89.
in muscles, 31, 36, 300.
maintenance of, 108.
of motor cycle, 118.
of muscle and engine compared, 30, 300.
Civilisation, effects of, 317.
Clerk, Sir Dugald, 30.
Climbing, use of arm in, 67.
Clothes, need for, 155.
use of, 158.
Clutches of muscular engines, 44.
Coal-gas poisoning, 121.
Cold, effect of, 155.
winds, effect of, 157.
Colds and catarrhs, 139, 158.
Colic pains, 216.
Colon, 195, 320.
digestive changes in, 210.
Columbus's discovery, 106.
Combustion and life, 148, 277.
and respiration, 151, 299.
chamber, 11.
chambers of body, 150.
of muscles, 35.
in lungs, 141.
material, circulation of, 32, 119.
nature of, 31, 148, 277.

Combustion, relation to work, 113, 286, 313.
Communication, systems of, 221.
Compensating mechanism, 60, 271.
Complex muscle, 50.
Compression stroke, 12.
Connecting-rod, 9.
Consciousness, 238, 331.
Constipation, 218.
Contraction of striated muscle, 36.
  wave in œsophagus, 177.
  waves, regulation rate of, 192.
Convolutions of brain, 238.
Cooking, effects of, on body, 217, 317.
Cooling of engine, 33.
  systems, 33.
Co-ordinating machinery, 220.
Coracoid process, 28.
Corpus callosum, 237.
Corpuscles of bone (see Bone-builders).
Cortex of brain, 238.
Costal cartilages, 125.
Coughing, 139.
Cramp of writers, 68.
Cranial capacity, 235.
  chamber of battleship, 252.
  nerves, 241.
Crank-pin, 9.
  heel as, 61.
Crile, Prof. George, 226.
Culmann, Prof., 76.
Cure, the conditions of, 268.
Cutis or true skin, 155.

Dalby, Prof. W. E., 314.
Darwin, Charles, 327.
Dead-centre, problems of, 61.
Degeneration of great bowel, 216.
  of jaws, 167.
Dendrites, 250.
Dephlogisticated air, 149.
Design in bone structure, 79.
Detectives, medical men as, 106.
  methods in anatomy, 247.
Dewar, Sir James, 5, 276.
Diabetes, 321.
Diaphragm, 129, 131.
Diastole of arteries, 94.
Diet (see also Food).
  of ancient man, 216, 320.
Digestion affected by mental states, 184.
  as source of heat, 154.
  blood supply during, 116.
  in great bowel, 210.
  in stomach, 188.
  intestinal, 197.
  movements of, 183.
  powers of, 184.
Digestive system (see Alimentary).
Discovery, Harvey's guide to, 99.
  methods of, 107, 245.
Drip-feed system, 81.
" Driver " cells, 257, 262, 288.
Drowning, recovery from, 242.
Drug-taking, 218.
Duodenum, 183, 195.
Dwarfs, 74.

Ear, functions of, 234, 289.
Ebb and flow a law of Nature, 95.
Economy in design, 79.
Edkins, Prof., 188.
Education of muscles, 39, 40, 287.
Efferent nerves, 246.
Efficiency, standard of, 48, 313.
Effort, effects on body of, 118, 284, 296, 306.
Elastic coat of arteries, 112.
Elasticity lost by age, 112.
Emotional centres, 240.
End plates of nerve fibres, 37.
Energy ration, 160.
Engine, dead-centre explained, 61.
" Engine-eaters," 34.
Engineer as anatomist, 56.
Engineering difficulties in bone-building, 70.
Engineers, bone corpuscles as, 75.
Engines, peculiarity of living type, 60, 276.
  reciprocal, 41.
Enzymes, 197, 283.
Epidermis, 155.
Epiphyseal lines, 73.
Epiphyses of bone, 72, 292.
Epithelium of bowel, 205.
Erect posture, blood supply in, 117.
    maintenance of, 287.
    maintenance of spine, 24, 332.
Eunuchs, 229.
Evaporation as means of cooling, 156.
Exchange centres (see also under Reflex and Nerve Centres), 254, 287, 329.
  terminals, 255.
Exercise, effect of, 64, 145, 283, 296.
    on bowel, 204.
    on breathing, 121, 153, 307.
    on combustion, 143, 152, 276, 297, 312.
  influence on circulation, 114.
  is necessary for muscles, 38, 46.
Exercises for stiff joints, 88.
Exhaust pipe, 11.
    compaired to vein, 29.
    of human body, 122.
  stroke, 13.
  valve, 11.
Explosion chamber, 11.
  stroke, 12.
Explosive mixture (see also under Combustion), 11, 312.
Eye, reflexes of, 254, 331.
  represented by camera, 232.

Fabricius, teaching of, 91.
Face, alterations in, 167.
Face at end of skull lever ,50.
Factor of safety law, 79, 144.
Fainting, 117.
Fairbairn crane, 76

Fan-like expansion of lungs, 144.
Faraday, 11.
  on combustion, 31.
Faraday's Christmas lectures, 2.
Fat as non-conductor of heat, 157.
Fatigue of muscles, 25, 279.
Fats, action of bile on, 202.
  as sources of heat, 154.
  digestion of, 188, 198.
Fauces, pillars of, 164.
Fear, effects of, 18, 225.
Feed-pipe, 11, 171.
  as alimentary system, 160.
Femur (see *Thigh Bone*).
Fermentation in bowel, 216.
Filtering of air breathed, 138.
Fingers, sheaths of, 87.
Fire, effects of invention, 217.
Fisher, A. T. G., 294.
Fixed air, 123.
Flack, Group-Capt. Martin, 153, 306.
Flat-foot, 63.
Fletcher, Sir W., 32, 277.
Float-chamber, 160.
Flying stress, 307.
Fly-wheel, use of, 13.
Food, amount required, 160, 315.
  as fuel, 159, 277, 313.
  effects of over-indulgence, 164.
  modern preparation of, 165, 217, 317.
  preparation of in mouth, 168.
Foods, 188.
  albuminous, 188, 314.
Foot, action of in walking, 20.
  arch of, 62.
  as lever, 57.
  mechanism of, 16.
Foramen magnum, 53.
Force-pumps, 109.
Forearm as lever, 64.
  movements of, 29.
Fracture of bone, 79.
  repair of, 73, 79, 271.
Friction, methods of obviating, 86.
Fuel for muscles, 157, 277, 312.
  or food, 159, 314.
  preparation of, for body, 198.
Function, specialisation of, 133, 264.

Gall-bladder, 201.
Games as educators of muscles, 40, 287.
Ganglion, posterior root, 240.
Gas, formation of in bowel, 216.
Gastric juice, 187.
Gastrin, 188.
Gastrocnemius, 14, 58.
Gearing as illustrated by heel, 60.
Gearing of muscular engines, 44.
Giantism, 227.
Giants, growth in, 75.
Glands of intestine, 198.
  of internal secretion, 75, 321, 325.
  of stomach, 186.
Glottis, 136.
Glycogen, 201, 277, 282, 314, 321.
Government officials of the body, 265, 327.
Growth discs of bone, 73.
  disorders of, 74, 75.
  effected during work, 64.
  harmony necessary, 70.
  in bone, 70, 73.
  regulation of, 225.
  responses, 228.

Haldane, Dr J. S., 143, 301.
Hales, Stephen, 112.
Hall, Dr Marshall, 247.
Hamstring muscles, 17.
Hand in climbing, 67.
  muscles used in steadying, 40.
Happiness, a source of, 219.
Harvey on use of lungs, 147.
  story of life, 88, 97.
Harvey's experiments, 104, 295.
Head as a lever, 50.
  balancing of, 25.
  movements of, 52.
  of pressure in arteries, 109.
  rotatory movements of, 55, 289.
Head, Dr Henry, 239.
Healing, mechanism of, 367.
Health, in relationship to bowel, 203.
Heart, a master-pump, 109.
Heart and mechanical pump compared, 110.
  apex of, 95.
  as pump, 89, 102.
  as pump for engine, 31.
  as source of life, 93.
  blood-supply of, 296.
  chambers of, 94.
  disease, 271.
  load of, 105, 295.
  movements of, 102.
  nerve control of, 114.
  nodal centre, 192.
  pistons of, 109.
  position of, 130.
  rate of, 114, 276, 304.
  represented in motor cycle, 119.
  structure of, 100.
  valves of, 100.
  work of, 113, 295.
Heat, escape of from body, 156.
  food values for, 160, 314.
  generated in muscles, 32, 280.
  heart as source of, 93, 296.
  measurement of, 277.
  production of in body, 152.
  regulating mechanism, 146.
  stroke, 157.
Heath, Mr J. W., 5.
Heating systems for engines, 33.
Heel as crank-pin, 14.
  as lever, 58.
Hiccough, 180.
High altitudes, life at, 297.
  heels, effect of, 18.
Hill, Prof. A. V., 279, 285, 296.
Hill, Dr Leonard 117, 153, 157.

Hip-bone, mechanism of, 19.
Hip-joint, action of, in walking, 19.
His, Prof. Wm., 250.
Hopkins, Prof. Sir F. G., 32, 279, 310.
Hormone, carbon dioxide as, 143.
of stomach, 188.
theory, 222.
Hormones, 311, 321, 328 (see also Secretin).
action on pylorus, 191.
in disordered growth, 75.
Human body compared to army, 221.
compared to motor cycle, 8, 26, 41, 118, 283.
compared to society, 326.
effects of civilisation on, 317.
its future state, 219.
its government service, 264, 328.
unit organisation of, 230, 274.
Humerus as lever, 67.
Hunger, a warning signal, 162.
effect on digestion, 188.
Hunter, John, 229, 244, 289.
observations on digestion, 189.
Hydraulic problems, 109.
Hydrocarbons, 31, 277, 312, 324.
Hydrogen, discovery of, 149.
Hypertrophy from overuse, 179.
Hypophysis (see Pituitary Gland), 224.

Ileo-cæcal orifice, 211.
sphincter, 195.
Ileum, 195.
Immunity of stomach to digestion, 189.
Infant as engine-driver, 39.
Infection of wounds, 269, 273.
Infections favoured by cold, 158.
Inlet pipe, 11.
valve, 11.
Inogen, 277.
Insertion of muscles, 15.
Insulin, 283, 321, 325.
Intellect, 239.
Intercostal muscles, 129.
Internal-combustion engine and muscle compared, 29, 276, 297, 312.
engine, model of, 5.
engine, reconstruction of, 10.
engine, respiratory chamber of, 133.
Internal secretion, glands of, 224, 321.
secretions, 75.
Interstitial gland, 224.
Intervertebral discs as buffers, 22.
Intestinal factory, 196.
tailrace, 206.
Intestines (see Bowel).
Iris diaphragm mechanism, 111.
Irvine, Mr A. C., 306.

Jaw, lower, 165.
upper, 165.
Jaws, alterations from use, 167.
remodelling of, 166.
Jejunum, 202.
Jiu-jitsu, 51.
Joint between skull and spine, 52.
Joints, anchylosis of, 87.
construction of, 80.
end organs of, 256.
how they are guarded, 54.
manipulation of, 270.
of body, 82.
wear of in disease, 87.

Keith's experiment, 150.
Kellas, Dr A., 301.
Kidneys, function of, 201.
Knee-joint, displaced cartilages, 270.

Labour, adaptations for, 68.
Labyrinth, 289.
Lachrymal gland, 255.
Lacteals, 187, 204.
Lactic acid, as degradation product, 279, 284.
Laryngeal orifices, 136.
Larynx, 136.
drawing of, 176.
Lavoisier, 150.
Left ventricle (see Ventricle).
Leg, muscles in front of, 17.
Legs as wheels, 26.
Leucocytes or white corpuscles, 230, 328.
Lever of first order, 48.
lower jaw as, 166.
of second order, 57.
of third order, 64.
Levers, formation of, 70.
of skeleton, 47.
of vertebræ, 23.
Lewis, Sir Thomas, 111.
Life, a form of combustion, 147.
Ligament, use of, 54.
Limbs, nerves to, 241.
Lipase, 198.
Liver, action of adrenalin on, 118.
action of insulin on, 324.
as source of heat, 152.
functions of, 200, 324.
position of, 131.
products of digestion to, 190.
supposed function, 91.
Living matter not digested, 189.
Locomotion in man and beast, 19.
Locomotive system, weight of, 89.
Lower, Dr Robert, 148.
Lower limb, muscles of, 17.
limbs compared to a wheel, 26.
Lubricant, formation of, 85.
Lubrication system, 80.
Lung, microscopic structure of, 139.
Lungs, area of lining membrane, 140.
capacity of, 140, 308.
circulation in, 102.
discovery of function of, 147.
expansion of, 144.
nature of, 120.
old conception of, 93.
position of, 130.
structure of, 137.
supposed heat regulators, 147.

Lymph, 187.
Lymphatics of stomach, 186.
Lymphoid tissue, 215.

Macalister, Prof. A., 89.
M'Collum, Dr, 310.
Macfarlane, Prof. J. M., 312.
Mackenzie, Sir James, 271.
Macleod, Prof. J. J. R., 322.
Magendie, 247.
Magnus, Dr R., 290.
Maihle, Prof. A., 313.
Mallory, Mr E. L., 306.
Malpighi, 105, 148.
Mandible (see Jaws).
Marie, Dr Pierre, 227.
Mass movements in colon, 209.
Mastication, 165.
  joints involved in, 82.
Mayow, Dr John, 148.
Medulla oblongata, 51, 237.
Medullary centres for heart, 114.
Mellanby, Dr and Mrs, 310.
Metchnikoff, 216, 320.
Meyerhof, Dr O. 280.
Microscope, use of, 105, 249, 326.
Mill, jaws used as, 165.
Mind, effect of, on digestion, 184.
Mitral valve, 103.
Motor centres of brain, 262.
Motor cortex or administrative areas, 239.
Motor cycle, alimentary canal of, 160, 196.
    and human body compared, 8, 26, 41, 118, 230, 268, 276, 312.
    circulation in, 118.
    co-ordinating mechanism of, 220.
    defect of, 60.
    design of frame, 79.
    efficiency compared to that of body, 160, 313.
    levers of, 47.
    mechanism of, 9.
    respiratory system of, 123, 133.
    suffocation of, 124, 279.
    systems of lubrication, 81.
Motor functions of brain, 233.
  impulses, 257.
Mount Everest Expedition, 301, 306.
Mouth, 162.
Mouth-breathing, 136.
Mouth, construction of, 164.
Movements, regulation of, 33, 287.
Moynihan, Sir Berkeley, 191.
Mucous epithelium of bowel, 205.
  glands of air-passages, 138.
    of mouth, 168.
  membrane of bowel, 198.
Muscle, combustion in, 151, 276.
  cylinder, 35.
    combustion chambers of, 35, 281.
    compared to engine, 35.
  cylinders of heart, 110.
  evolution of, 264.
  fibres, non-striated, contracted, 177.
Muscle in action, 28, 36.
  microscopic structure of, 34.
  non-striated, of bowel, 172.
    relaxation of, 178.
  of bronchioles, 137.
  spindles, 41.
  structure of, 29.
Muscles, adaptation of, 227.
  antagonistic action of, 128.
  as engines, 13, 276, 312.
  as guardians of joints, 83.
  as internal-combustion engines, 31, 38, 276.
  as motor engines, 8.
  as " pull " engines, 15.
  as reciprocal engines, 41.
  attachment of, 14.
  care of, 38, 39, 45, 64, 291.
  circulation in, 29, 31, 116, 300.
  educated by games and sports, 40, 291.
  efferent messages from, 262, 289.
  efficiency of, 315.
  elongating action of, 18.
  employed in locomotion, 25.
  fatigue of, 25, 279.
  influence of adrenalin on, 118.
  influence on circulation, 115, 284.
  learning control of, 39, 291.
  merits of, as engines, 44, 283.
  nature of combustion in, 32, 280.
  nerve impulses to, 37, 257, 287.
  nerve mechanism of, 81, 260, 287.
  noise of, 44.
  of abdomen, 129.
  of lower limb, 17, 20.
  of respiration, 127, 283.
  paralysis of, 38.
  temperature of, 34, 280.
  timing of action, 17.
  weight of, 26, 89.
Muscular contraction, chemistry of, 2
    sound of, 44.
  effort, mechanism of, 225.
  engines always running, 44.
    peculiarities of, 18.
    readiness of, 44, 283.
  fibre, structure, 35.
  nodes, 192.
Musculi papillares, 100.
Myelin, 249.

Nasal cavities, 134.
Natural spirits, 91.
Nature as healer, 268.
  perfect designer, 99.
Neck, evolution of, 56.
  muscles of, 57.
Negro, heel of, 59.
Nerve cell compared to battery, 256
  cells, 241.
    discovery of, 250.
    need of oxygen supply, 242, 325.
    need of sugar-supply, 325.
    of brain, 237.
    of spinal cord, 261.

Nerve centre of vomiting, 192.
centres for bowel, 204.
for great bowel, 219.
for lungs, 137.
for skin, 156.
for stomach, 186.
for swallowing, 176.
for taste, 163.
current, 256.
endings as transmitters, 253.
end organs (see Transmitters).
of muscles, 43.
exchanges, construction of, 257.
for muscles, 43, 287, 330.
fibres, 241.
as living wires, 255.
structure of, 249.
impulses, rate of, 260.
mechanism of heart, 114.
of muscles, 43.
of œsophagus, 178.
of secretion, 168.
of skin, 155.
messages from muscles, 41, 289.
nature of, 260.
to muscles, 37, 332.
"operatives," 238, 330.
roots, development of, 250.
system compared to telephone, **252**, 329.
evolution of, 264.
unit compared, 255.
Nerves compared to electric wires, 30.
degeneration of, 248.
discovery of uses, 244.
effect of section, 38.
function of, 243.
influence of, on muscles, 37.
of heart, 114.
repair of, 249.
spinal and cranial, 240.
to muscles, 30.
Nervous system, nature of, 222.
Neuron theory, 251.
Nodal centres, 192.
for bowel, 202.
Nose, nerves of, 244.

Occipital areas and pole of brain, 239, 332.
condyles, 53.
Œsophagus, constriction of, 179.
length of, 173.
passage of food along, 173.
structure of, 177.
Old age, vertebral changes in, 22.
"Operative" nerve cells or units, 251, 259, 288.
Optic nerves, 233, 331.
thalamus, 239, 262.
Ossification, 70, 292.
Osteoblasts (see Bone-builders).
Overheating of engines, 33.
of joints, 80.
Oxygen, absorption of, 142, 299.
consumption of, 285, 295.
Oxygen, conveyance of in blood, 32, 120, 300.
discovery of, 149.
"Oxygen starvation," 121, 297.

Padua, University of, 91.
Pain, centres for, 239.
mechanism of transmission, 262.
Palate, satisfaction of, 160.
soft, 174.
Pancreas, 199, 322.
Pancreatic secretion, 199.
Paralysis of muscles, 38.
Parker, Dr Rushton, 308.
Pelvis (see Hip-bone).
as respiratory base, 128.
Peristaltic waves, 203.
Peritoneum, 202.
Peroneal muscles, 16.
Petrol, heat value of, 277, 314.
of sharks, 161, 313.
supposed origin of, 161, 312.
tank, 11.
as stomach, 160.
Phagocytes, 139.
Pharyngeal sphincter, 174.
Pharynx (see Throat).
traffic in, 174.
Physicians, College of, 99.
Pineal gland, 224.
Piston-like action of diaphragm, 129.
"Pit of the stomach," 132.
Pituitary gland, 75, 224, 227, 325.
Pivot of axis vertebra, 55.
Police service of body, 215.
system of colon, 211.
Portal circulation, 203.
vein, 91, 200.
Postal system of the body, 199, 220.
Postural reflexes, 287.
Power gained at expense of speed, 51.
Priestley, Joseph, 149.
Protection from infection, 211.
Protective mechanism in great bowel, 214.
Proteids, 189, 314.
digestion of, 198.
Pulmonary artery, 101.
circulation, 142, 300.
vessels, 93, 102.
Pulse of bowel, 202.
of stomach, 183.
waves, regulation of rate, 192.
Pump, construction of, 109.
system of body, 59.
Pump-action of internal-combustion engine, 13.
Pumps in alimentary canal, 171.
"Push" versus "pull" engines, 42.
Pylorus, mechanism of, 180, 190.

Quadriceps muscle, 20, 288.

"Rabbit mouth," 317.
Radiators, 134.
Radius of forearm, 29.

"Receiver," nature of, 255.
Reciprocal action of muscles, 51.
engines, 41.
Rectum and vent, 208.
reflexes of, 218.
Red blood corpuscles, 142.
as carriers of oxygen, 300.
Reflex action, discovery of, 248.
explained, 253.
actions (see also "Touch-button Mechanisms).
actions, 234.
mechanism of heart, 114.
of pharynx, 174.
Repair of bone, 73, 272.
Repairs, execution of, 64, 267.
Residual air, 141, 307.
Respiration, 120, 297.
antagonistic action of muscles, 128.
at high altitudes, 298, 303.
defined, 123.
discovery of nature of, 150.
in lungs and in engine, 141, 301.
in motor cycle, 122.
muscles of, 127, 129, 282, 300.
old conception of, 93.
rate of, 123, 308.
retarded by shoulders, 124.
volume of, 308.
Respiratory chambers, 137, 138.
exchange, 142, 299.
effect of exercises, 153, 284.
in muscles, 32, 282.
exercises, 144, 307.
"governor," 303.
movements, 125, 128.
nerve-centres, 143.
passages, 134.
cleansing of, 138.
Rest is necessary for muscles, 45, 285.
needed by nerve cells, 263.
Resuscitation, 242.
Reversed action in muscles, 68.
Rheumatic changes, 87.
Ribs, arrangement of, 125.
as balancing levers, 23, 126.
attachments of, 23.
Rickets, 74, 312.
Roberts, Mr Morley, 275, 328.
Röntgen's discovery, 184.
Rotation of head, 84.

Saliva, formation of, 168.
Scapula (see Shoulder-blade).
Scheele, 149.
Sea-sickness, 193.
Sebaceous glands, use of, 157.
Secretion, 199, 223.
mechanism of, 168.
of gastric juice, 188.
Seizing of joints, 86.
Self-repairing power of living engines, 46.
Sequeira, Dr James, 230.
Servetus, 103.
Sex glands, 224.
influence on growth, 229.
Sewage system of body, 187.
Sexual impulses, 162.
prematurity, 229.
Sherlock Holmes in Medicine, 106.
Sherrington, Sir Charles, 287.
Shivering, effects of, 154.
Shoulder-blades, fixation of, 25.
Shoulders, suspension of, 125, 332.
"Signaller" cells, 257, 287.
Signalling in alimentary system, 191, 209.
Sinews, 16.
Singing, control of muscles in, 128.
Sitting, muscles involved in, 21.
Skeleton, bones of, 71.
compared to framework of bicycle, 14.
in motion, 14.
weight of, 89.
Skin, area of, 156.
as heat regulator, 155.
shedding of epidermis, 85.
structure of, 155.
Skull as lever, 50.
Sleep needed for repair, 263.
Smell *mechanism*, 135.
sense of, 163.
Smith, Prof. G. Elliot, 239.
Soleus (see Gastrocnemius).
Sparking plug, 9, 11.
"Sparking plugs" of muscles, 37.
Speaking, control of muscles in, 128.
Specialisation exemplified, 133.
Speech, 136.
action of tongue in, 165.
beginnings of, 39.
Speed gained at expense of power, 49, 65.
optimum of, 286, 313.
Speed-gear problems, 60.
Spencer, Herbert, 327.
Sphincter at cardiac orifice, 173, 179.
ileo-cæcal, 195.
mechanism of bile duct, 202.
mechanisms, 161, 179.
of pharynx, 174.
of pylorus, 190.
Spinal column (see Back-bone).
cord, 237, 240.
reflex centres of, 259.
muscles act in respiration, 127.
nerves, roots of, 240.
roots, functions of, 246.
Spinous processes, 23.
"Spirits," 91.
Sprains, 87.
Springs of the body, 23.
"Stand at ease," significance of, 25.
Standard of efficiency for muscles, 45, 160.
Standing, exhaustion from, 25, 63.
Starch, heat values of, 314.
Starches, *digestion* of, 197, 311.
Starling, Prof. E. H., 115, 222.
Stature, completion of, 73.
Stomach, air in, 216.
as a hopper, 194.

Stomach, blood supply of, 117.
cardiac sphincter of, 179.
construction of, 185.
emptying of, 183.
filling of, 163, 181.
movements of, 182.
supposed function, 91.
vessels and nerves of, 186.
Stonehenge, leverage at building of, 48.
Stopcock action in arteries, 113, 204.
mechanism, 115.
of lungs, 137.
system (see also Sphincter).
Stopcocks of heart, 111.
Strikes impossible in the body, 266, 328.
Stroke of muscle and of engine compared, 30.
regulation of length of, 32.
Strokes of internal-combustion engine, 12.
Structure, a guide to function, 99.
Struts and ties, 75.
Stump, Dr C. W., 292.
Suffocation, ancient explanation, 93.
methods of, 120.
Sugar, absorption of, 197.
as food, 315.
as fuel for muscles, 37, 159, 315, 324.
in blood, 321.
produced in liver, 118, 226, 324.
tolerance of, 325.
Suprarenals (see Adrenals).
Surgeon's rôle in healing, 268.
Swallowing, 168, 173.
Sweat glands, 156.
Sweet-bread (see Pancreas).
Swimming, joints involved in, 82.
Synovia, 84, 294.
absorption of, 86, 295.
Synovial sheaths, 87.
Systole of arteries, 94.

Taste-buds, 163.
Taste, mechanism of, 163.
Teeth, 166.
, decay of, 167, 318.
nerves of, 169.
replacement of, 166.
toilet of, 168.
Telepathy, 266.
Telephone exchanges, 252.
in nerve system, 257, 287, 329.
system of body, 253.
unit explained, 255.
Telescope, joints of, 53, 56.
Temperature (see also under Heat).
regulation, 34.
skin regulation of, 155.
Tendons as piston-rods, 15.
repair of, 268.
sheaths of, 87.
Test-meal of bismuth, 170.
Test-tube glands, 198.
Theory, nature of, 107.
Thermopile, 280.
Thigh-bone, architecture of, 75.
Thigh-bone, growth of, 70.
repair of, 272.
Thirst, 157, 162.
Thorax as bellows, 120, 130.
joints of, 83.
structure of, 125.
Throat, 135.
construction of, 174.
functions of, 173.
involuntary movements of, 163.
mechanism of, 175.
Throttle-valve, 11.
"Throttle-valve" of muscles, 38.
Throttle-valves of body, 153.
Thyroid gland, 224, 226.
secretion, effects on combustion, 154.
Tidal air, 141.
Timing of muscles, 17.
systems, 220.
Tired muscles, 18.
Tissues, nourishment of, 108.
Tongue, 163.
actions of, 165, 169.
Toothache, 169.
"Touch-button" machinery, 180, 248.
mechanism of rectum, 218.
of throat, 175.
telephone mechanism, 253.
Toxin formation, 211.
Trachea or windpipe, 93, 121, 136.
Transmitters explained, 254.
in muscles, 43, 287.
or end organs, 175.
Transmitting stations of mouth, 169.
Transport in intestines, 202.
system, 159.
Transverse processes, 23.
Triceps muscle, 41.
Trochanters of femur, 72.
"Trunk" calls to the brain, 159, 261.
Trypsin, 198.
Tubular boiler, exemplified, 204.
Two-cycle engine, 30.

Unborn child, 70.
Upright posture (see Erect Posture).
Urea, formation of, 201.

Vagus nerve, 241.
Valve trouble, 271.
Valves of engine, 11.
of heart, 99.
of pump, 109.
of veins, 97.
Vaso-motor mechanism, 115.
of bowel, 204.
system, 226.
Veins, 91.
as exhaust pipes, 29.
Ventricle, left, as pump, 103, 109.
Ventricles of heart, capacity of, 105.
Vertebra, parts of, 54.
Vertebræ, 22.
first and second, 55.
Vestigial structures, nature of, 213.
Villi of intestine, 204.

Viscera in diaphragmatic piston, 131.
support of, 129.
Vision, 232.
Visual cortex, 238.
Vital capacity of lungs, 141, 307.
spirits, 93.
Vitamins, 308, 319.
Vocal cords, 136.
Voice, training of, 41.
Vomiting, mechanism of, 192.
Von Mehring, 322.

Walking, action of backbone in, 21.
joints involved, 82.
mechanism of, 14, 16.
nerve mechanism of, 253, 287.
racial gait in, 60.
Waller, Dr Augustus, 248.
Warfare between cells, 73, 328.
Warming chambers, 134.
Warning-horn of human machine, 136.
Water, discovery of composition of, 149.
passage of, in the stomach, 183.
Water-taps, 115.
Weight of bones and muscles, 89.
of left ventricle, 110.
of muscles of adult man, 26.
Wheel, nature of, 14.
Wheels compared to limbs, 26.
Wind in alimentary system, 216.
Windpipe (see Trachea).
Wireless installation, 266.
Woman, brain of, 235.
Work (see also Exercise).
efficiency of, 286, 315.
food transformed into, 160.
fuel and oxygen needed for, 113.
Wounds, repair of, 269, 273.
Wrist, fixation of, 68.
Writer's cramp, 68.
Writing, muscles concerned in, 40.

X-ray examination, 170.

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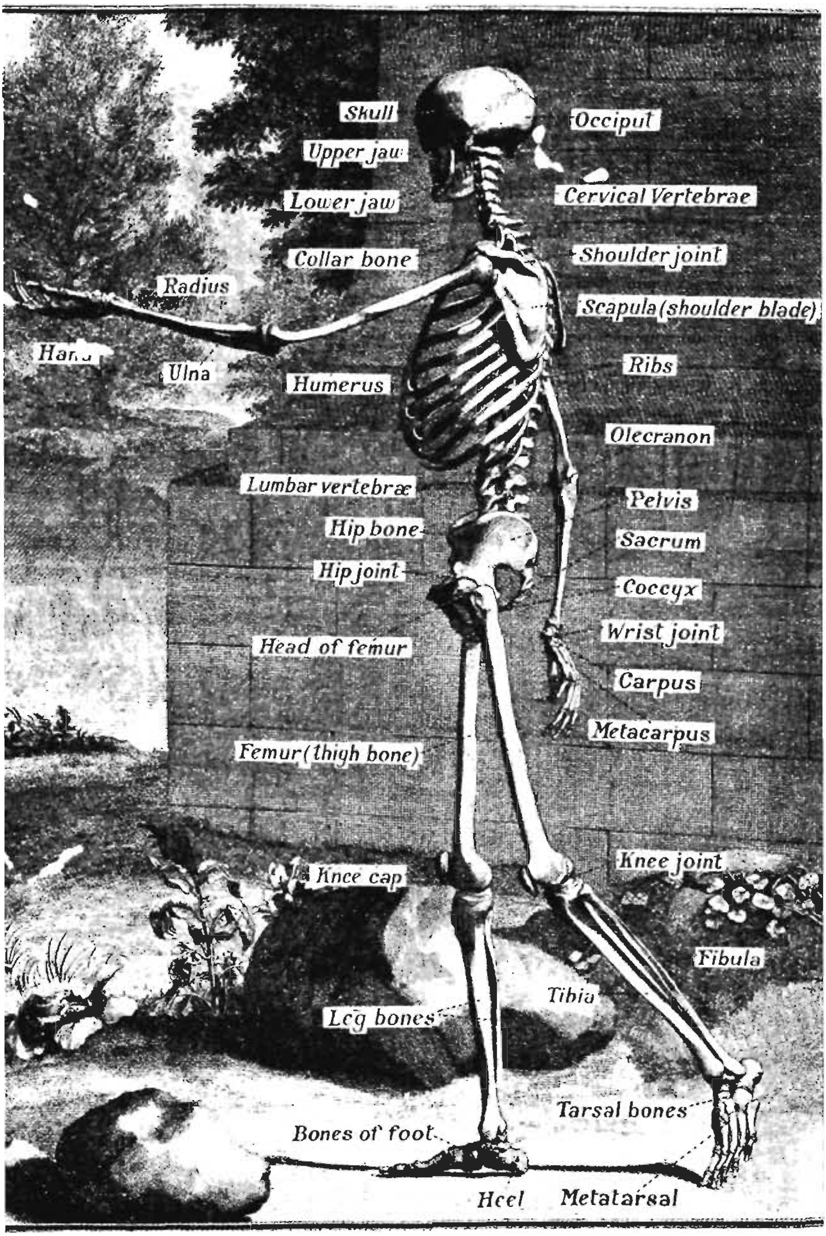

PLATE I.—The walking human skeleton (Albinus).

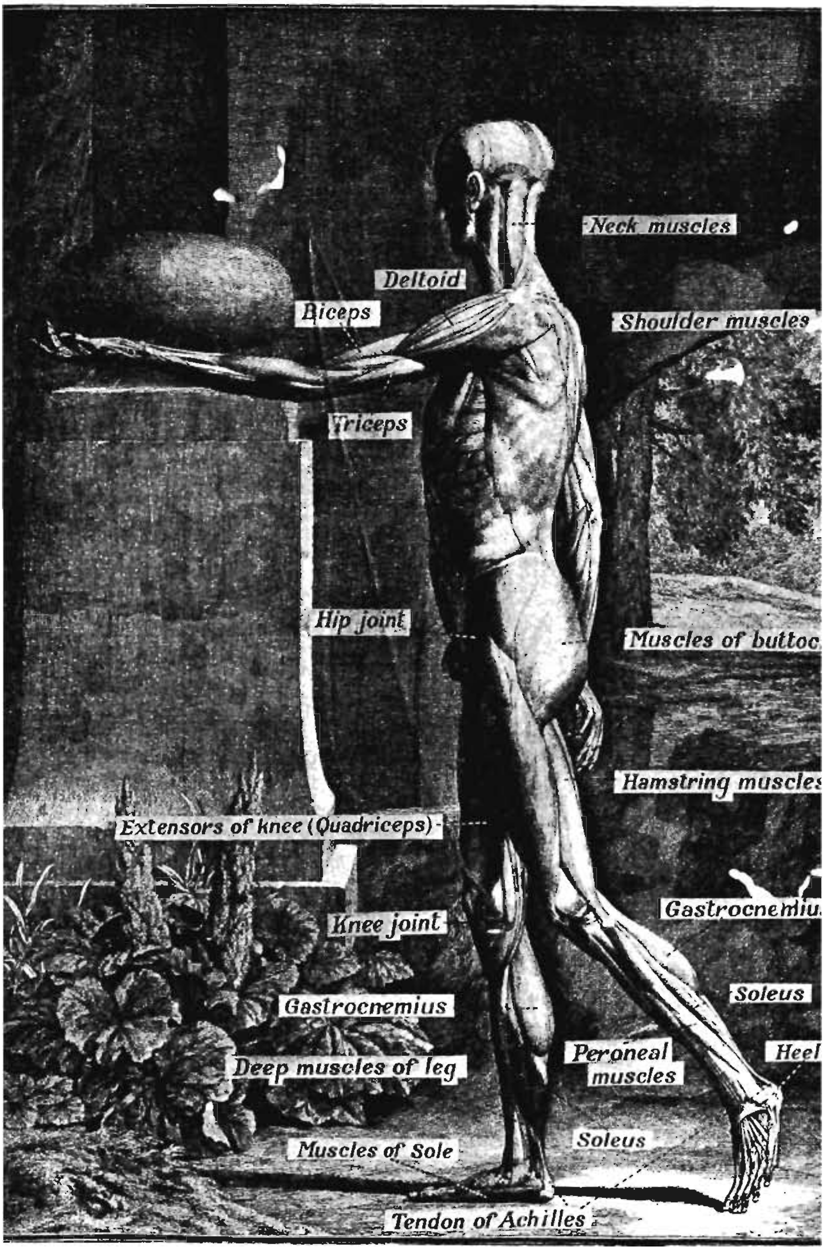

PLATE II.—The muscles of the human body (Albinus).